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ANALYSIS OF DESIGN-RELATED PROBLEMS
FROM AN INDUSTRIAL PROJECT

Publication No. _____

John Richard Glavan, Ph.D.
The University of Texas at Austin, 1988

Supervising Professors: Richard L. Tucker
James T. O'Connor

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* The problems were identified and classified into eight categories through the Inter-Office Memos which originated from the construction site. Problems are graphically displayed for each problem category, organization of the problem originator, and discipline for each of the four process areas. The results show that the timing and number of problems for each unit

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are similar throughout the construction phase of the project.

Problem dependencies between problem categories, organization, and discipline are shown through the use of contingency tables. Problem deviations are analyzed by testing the hypothesis that the percentage of problems are linearly proportional to the percentage of discipline progress complete. Results showed that Civil problems occurred early in the project. Piping and Electrical problems increased linearly in proportion to the progress complete. Equipment and Structural problems followed a pattern which showed problems developing at the end of the discipline's activities. Instrumentation, a changing technology, showed the most scatter, but tended to follow the same type of pattern as Equipment.

Forecasting models are developed using regression analysis. Three models are developed to predict the potential number of design-related problems: 1) a model using design manhours, 2) a model using construction manhours, and 3) a model using the discipline's progress schedule. A time series model is tried, but the results indicate that this method is not appropriate to analyze these problems.

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ANALYSIS OF DESIGN-RELATED PROBLEMS
FROM AN INDUSTRIAL PROJECT

by

JOHN RICHARD GLAVAN, BSCE, MSE

DISSERTATION

Presented to the Faculty of the Graduate School of
The University of Texas at Austin
in Partial Fulfillment
of the Requirements
for the Degree of
DOCTOR OF PHILOSOPHY

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The opportunity to complete my studies was sponsored by the U.S. Air Force Academy through the U.S. Air Force. I appreciate the encouragement of Colonel David O. Swint, Professor and Department Head of Civil Engineering, U.S. Air Force Academy.

The advice and guidance of my dissertation committee, particularly Dr. Richard L. Tucker, proved invaluable while analyzing the project's data and preparing the dissertation. I felt as if they were there to help me and were working towards a successful completion of this study.

Finally, I would like to thank my wife and family for their encouragement as well as their insistence upon outside activities that helped keep this work in proper perspective.

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CHAPTER 1

INTRODUCTION

1.1 Background

Industrial construction projects have always been driven by two major factors: the need to utilize the latest technology and the desire to have completed projects as quickly as possible. These factors have resulted in problems of undefined scope and changing design throughout the early phases of the projects as well as fast-track projects where the design is not completed before construction starts. The economics of completing projects early have historically outweighed any problems or costs that arose during the construction phases of projects. However, in today's market of rising production costs and decreased profit margins, owners are forced to carefully monitor expenses in all project phases.

These problems are discovered during the actual construction of the project, but the majority of these problems originate in the design phase. Currently, there is no documentation linking these problems to the design phase where the actual cause of the problem can be determined.

Before the cause can be investigated, a method must be established to identify and categorize these problems. To establish a method, documentation from a completed industrial project will be examined. This is the first step in establishing a link between problems discovered in the construction phase and their origination in the design phase.

1.2 Type of Research

There is an enormous amount of paperwork flowing from a construction site to the design office, but it is not being as efficiently utilized as it could be. There is also a lack of information from a completed project to the planners and designers of future projects. The main reasons for these deficiencies are that historical data are rarely reviewed and synthesized into useful information for future projects, and the existing data are not always in the most useful form.

Historical research has been defined as "the systematic search for documents and other sources that contain facts relating to the historians' questions about the past" (Borg and Gall 1983, 800). The key aspect of historical research is that the events or

project have been completed so that there is no possibility to design ongoing experiments and gather data while the project is taking place. The researcher must use what is currently available to complete the research.

Why do historical research? As stated by Wiersma,

Historical research can be useful for predicting future trends. There is an old adage that those who are unfamiliar with the mistakes of history are doomed to repeat them. Thus, historical research can provide information necessary to avoid previous mistakes. (Wiersma 1985, 184)

Why hasn't more historical research been done in the construction area? The biggest reason has been that the project documentation has not always been complete or useful once a project was completed. Other reasons are (1) a lack of time or emphasis by management--once a project is completed, personnel are quickly moved to another project, and (2) the fact that the industry is very fragmented--information is often deemed proprietary and no one wants to share information or results of a project, either good or bad, with potential competitors.

This study involves historical research of a completed industrial project and attempts to analyze

data from this project to show that useful information can be found in existing documentation. The project documentation is thought to be extremely good, so the research has the potential to discover significant relationships and provide a guide for future documentation and research.

1.3 Purpose

The purpose of this study is to examine existing documentation from a completed industrial project and to identify and analyze the design-related problems that occurred in the construction phase of the project. This analysis will provide the first step in trying to determine the cause of certain problems. Obviously, the findings of this study are limited due to the fact that the data is from one project; however, the findings should lay the groundwork for more research in this area.

The objectives to support the purpose are:

1. Identify and categorize design-related problems through existing documentation.
2. Examine data for specific relationships and trends. Determine if the type and timing of design-related problems are consistent, or dependent upon the process technology. Establish the discipline and organization of the originator.

3. Establish profile curves to examine when problems are discovered by each discipline and explain why these problems occur at this time.
4. Using discovered relationships and trends, explore methods for predicting potential problems on future projects by developing forecasting models.

1.4 Dissertation Outline

This dissertation is organized into seven chapters. Chapter 2 provides general background information on industrial projects. Specific project characteristics are described in Chapter 3. Chapter 4 details the methodology used in this study. Chapter 5 presents the results of the dissertation. The analysis is completed and forecasting models are developed in Chapter 6. Conclusions and recommendations for future research are made in Chapter 7.

CHAPTER 2

SCHEDULE-DRIVEN PROJECTS

The majority of industrial construction projects are schedule-driven. This implies that the owner is willing to pay more for the construction of a project in an attempt to complete the project quicker. Earlier completion means that revenue can be generated sooner. This viewpoint is reinforced in an Engineering News Record (ENR) special report which states:

Because technology is advancing so fast in nearly all fields, the competitive edge for most types of manufacturers will depend on how fast a new product is introduced and how much of the market it grabs before the competition catches up.

For that reason, most new industrial construction projects "are going to be schedule driven," says Edward R. Cailouette, head of operations for Daniel International Corp.'s Redwood City, Calif., office. (ENR,24)

Schedule-driven projects have led to a scheduling technique commonly referred to as fast-tracking or phased construction. This chapter examines the life-cycle of a project and the results on total cost that fast-tracking can have on a project. The actual time sequence established in one mega project completed in 1984 will be shown as an example. Finally, the design and construction sequence used in a typical

industrial project is reviewed so that the relationship and timing between different activities can be understood.

2.1 Life Cycle of a Construction Project

The goal of a corporation is to maximize stockholders' profits. To accomplish this, a need or potential market is identified and a project's life cycle begins. This cycle begins with a concept and ends with implementation of the idea. From inception to completion, a project follows a fairly sequential path. Since different organizations have different names, divisions, and activities for these phases, the following phases are identified (see Fig. 2.1) and described for this study.

- | | |
|-----|--------------------------------------|
| I | Preliminary Studies |
| II | Engineering Design Basis |
| III | Contractor Selection |
| IV | Detailed Engineering and Procurement |
| V | Project Construction |
| VI | Plant Start-Up |

Phase I is concerned with the feasibility of the project and the resulting economic implications. Preliminary scopes of work are developed. The owner plays the key role during this phase, and only economically attractive projects receive funds to continue.

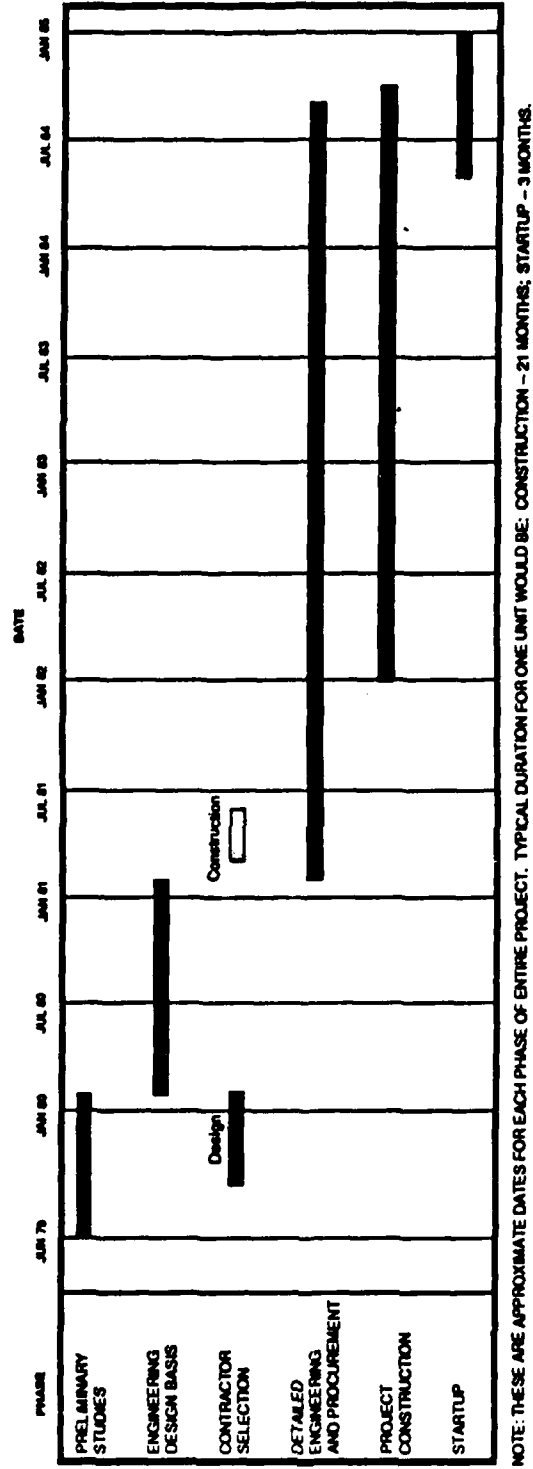


Figure 2.1 Phases of a Multi-Unit Construction Project

Feasibility studies and scope definition for this particular project lasted approximately 7 months (6/79 through 1/80).

The Engineering Design Basis (2/80-2/81) is also the owner's responsibility. During this phase, process units are defined, preliminary specifications are developed and reviewed, and environmental requirements identified. If still economically attractive, authorization for further funding is given.

Phase III involves the selection of a design contractor and a construction contractor. This can be the same firm as in the case of a "turnkey" project or two separate firms. The project described in this dissertation utilized separate contractors for design and construction. The selection of the design contractor took approximately five months. The construction contractor can influence the design through constructability if selected early enough (this will be discussed later). Of course, the longer it takes to select a construction contractor, the less impact he can have on the project's design. For this project, the construction contractor was selected by 6/81, several months prior to commencing construction activities.

During Phase IV, Detailed Engineering and Procurement, the remaining engineering design tasks are completed. These include detailed design, model building and review, definitive cost estimate development, and the procurement of long-lead items and any engineered equipment that will be furnished to the construction contractor. For this multi-unit project, this phase started in 2/80 (beginning with the first unit) and was completed in 9/84 (ending with the completion of design for the last unit) -- a total of 44 months.

Phase V is the actual construction of the facility. This project lasted 33 months for all units--from 1/82 until 9/84.

Phase VI is the plant start-up. During this phase, construction is completed and the facility is checked to see if the project has been built as designed, and if the units will operate as predicted during design. Modifications are sometimes made during this phase to optimize output or to ensure operability before turning the facility over to the user. The start-up of a typical unit takes approximately three months.

2.2 Influence on Costs

Most people are familiar with the cumulative S-curve of project cost throughout the life of a project and the second curve that shows the potential to influence the project's costs (see Fig 2.2). From this diagram, it is possible to observe that the greatest potential to influence costs occurs during the initial phases of the project. Since this is when the scope is relatively undefined, more emphasis must be placed on the feedback of past projects to try to control costs. Constructability and value engineering studies occur early in the project trying to accomplish this objective.

One of the objectives of this study is to determine if predictors of future problems exist to help management make early corrective actions to prevent schedule delays and cost overruns. Two types of predictors will be investigated: the first predictor will involve problems early in the construction phase of the project that will forecast potential problems which could be more costly to correct later on, and the second predictor will focus on the problems of one of the process units to determine if it can be used to forecast the potential

PROJECT EXECUTION

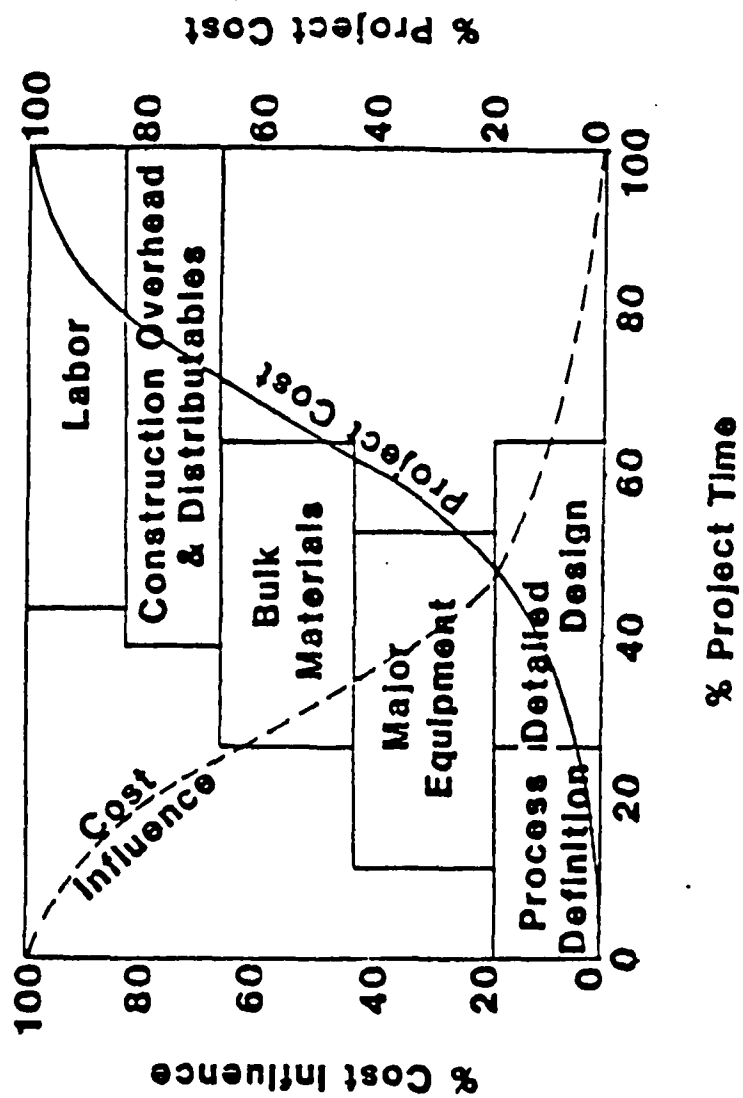


Figure 2.2 Cost Influence and Project Cost Versus Project Time (Reprinted from Smith 1983, 22)

problems that another unit might have. This will not be limited to the same type of process, but it is probably restricted to having the same owner and design contractor due to continuity of procedures. It is believed that the type and number of design-related problems will not be as greatly affected by a different construction contractor since each constructor would probably report the same problems.

2.3 Fast-Tracked Projects

As stated earlier, industrial projects are fast-tracked so that revenue can be generated quicker. Fast-tracking refers to the practice of overlapping the design and construction phases of the project instead of the traditional approach where the design is completed and construction is started after a contractor is selected following a period for bidding or negotiating. An example is shown in Fig. 2.3.

To determine the obvious advantage of fast-tracking, an analysis of the actual schedule for one unit was accomplished. For a typical unit, design takes approximately 32 months, construction 24 months, and start-up 3 months. If accomplished sequentially, the project would take 59 months. The actual project

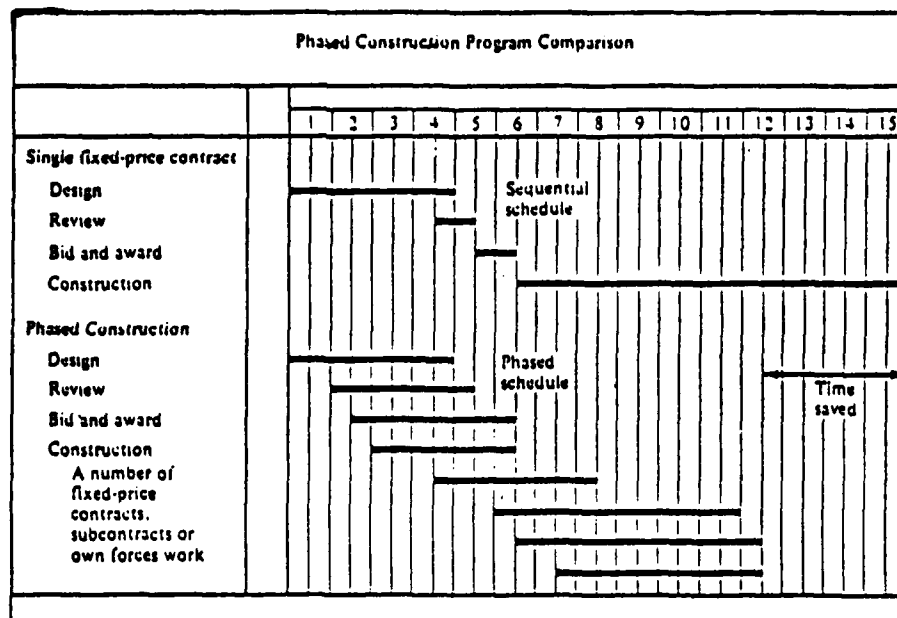


Figure 2.3 Example of Fast-Tracked Project.
(Reprinted from Barrie and Paulson 1984, 36)

started construction when the design was approximately 45% complete and was finished in 42 months for a savings of 17 months.

The disadvantage of a fast-tracked project is that an incomplete design leads to changes and errors in drawings, specifications, etc. which cause schedule delays and rework. The rationale for fast-tracking is that the cost of change orders and rework can be absorbed by the revenue generated by the product reaching the marketplace quicker. While this argument still holds true, owners are now exploring how fast-tracking can continue and yet avoid costly rework and schedule delays through better control procedures, early analysis, forecasting and trending. With the use of computers and other techniques, it is believed that more efficient management can reduce these problems. The result would be lower construction costs, smoother and shorter start-ups, and reduced schedules --all increasing a project's economic feasibility.

2.4 Sequencing of Fast-Tracked Projects

One of the key reasons that there may be a possible link between problems early in the construction process and those that occur later can be

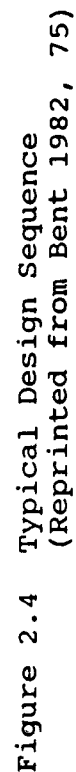
explained by the relationship between the design sequence and the construction sequence which overlaps it. This section discusses the design and construction sequences and examples are shown in Figures 2.4 and 2.5.

2.4.1 Design Sequence

During design, the process engineering starts the sequence. Process flowsheets, which define the process conditions throughout the system, are the heart of the job. Any errors in the flowsheets will be carried throughout the project (Ludwig 1974, 223).

Mechanical and utility flowsheets as well as preliminary plot plans are then developed. Detailed engineering is started with the client's approval of the process design, equipment layout (plot plan) and completion of the soil survey (Bent 1982, 65). First activities in the detailed engineering phase are foundation layouts, piping layouts and engineered equipment design. These activities are followed shortly by electrical, mechanical, structural and instrumentation engineering.

Design drafting is next in the schedule. Approximately three months after engineering design starts, foundation, structural and aboveground (a/g)



pipng drafting begins. Underground (u/g) facilities start when foundation design and a/g piping are 10% complete. Electrical and instrumentation drafting begin when a/g piping is at 10%. Building design starts when the foundation design is 10% complete (Hicks 1985).

The design/drafting effort continues with iterations between the design groups. The duration of the design phase continues on a fast-tracked project throughout most of the construction phase.

2.4.2 Construction Sequence

The construction sequence of a fast-tracked project closely follows the same sequence as the design/drafting effort. Civil work begins the construction phase of the project. This includes site preparation, foundations, paving and roadwork. U/G concrete lags the start of earthwork by 2 weeks and continues through about 50% of the construction phase. Structural work and pipe racks require foundations; therefore, they usually begin when foundations are 35% complete. Engineered equipment items are erected when 25% of the construction phase is reached. The towers and reactors are usually erected first, followed by drums and shell and tube exchangers. Air cooled

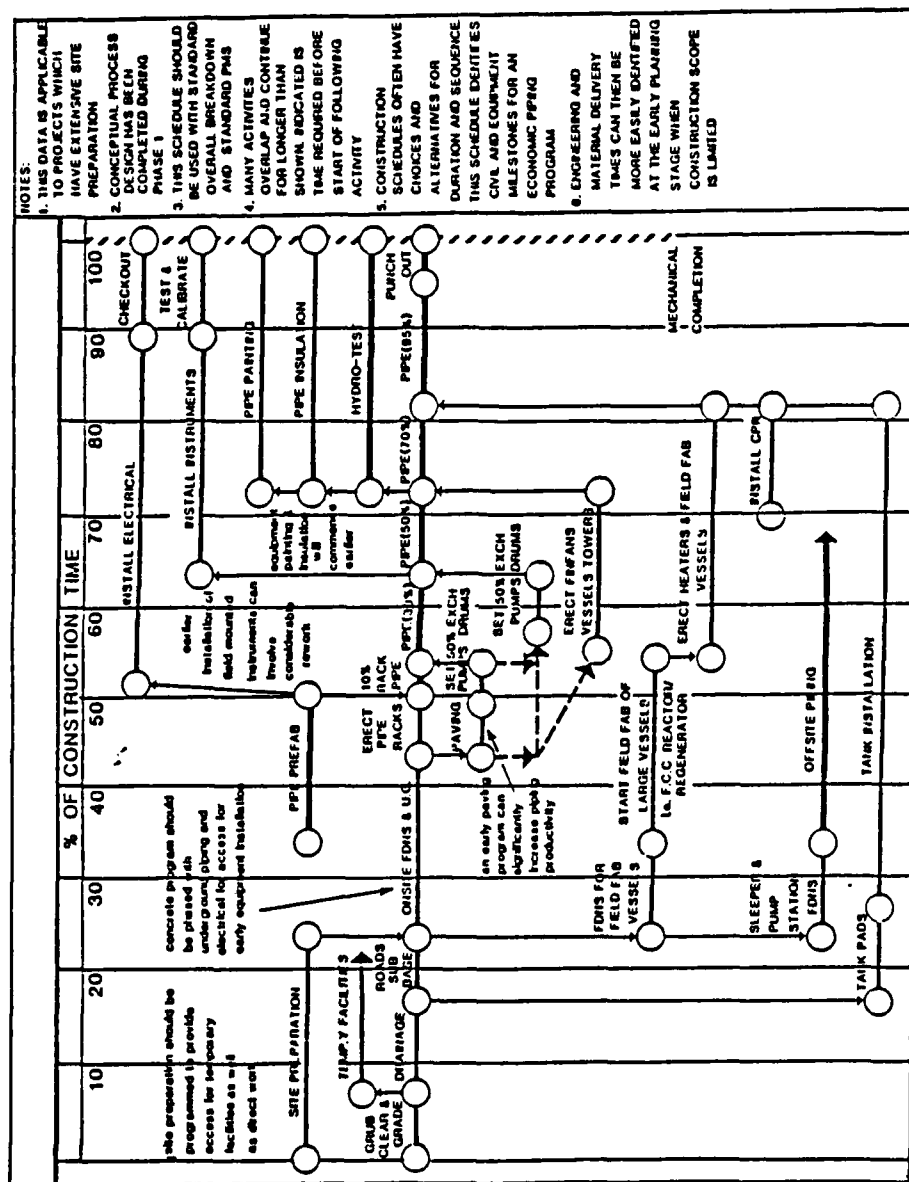


Figure 2.5 Typical Construction Sequence
(Reprinted from Bent 1982, 66)

exchangers are erected after the main pipe rack is completed since they are usually mounted atop the pipe rack. Compressors and pumps are started at the 40% point of construction and end with testing during the last 10% of construction. U/G piping starts after foundations are approximately 10% complete. U/G electrical lags u/g piping by about one month, but is completed at approximately the same time. A/G piping starts when the pipe racks are 65% complete (approximately the 40% point). A/G electrical begins when a/g piping is at 20%. Instrumentation lags both a/g piping (40%) and electrical (20%). Painting and insulation are normally done after equipment erection; however, on this project, these activities were scheduled to be accomplished earlier--while the equipment was at ground level. (This is an example of a constructability item and is discussed later.) Testing is continuous for each activity. It starts at the 50% point of each activity and runs until mechanical completion (Hicks 1985).

2.4.3 Summary

The design/drafting sequence has evolved to lead the construction phase in a fast-track project. All events are dependent upon accurate and timely

flowsheets. It is because of this dependency that problems in the beginning of construction may carry over to later phases of construction. Since design-related problems on a project originate from the same design team (including decision-makers, engineers, drafters, etc.), the hypothesis would be that the number and type of early problems can predict or explain part of the remaining problems. The alternate hypothesis would be that all problems are independent and there is no relationship between problems in the early stages and the problems encountered later. This will be examined in further detail in later chapters.

CHAPTER 3

PROJECT CHARACTERISTICS

Industrial projects represent approximately 25% of the construction market. Individual projects are usually very large and are designed and constructed by some of the largest design and construction firms.

In relation to normal projects, all problems such as technical complexity, scheduling, and cost are staggering. To help put this in perspective and to give a better appreciation of the difficulties that must be overcome to successfully complete this type of project, this chapter provides the background material on the particular project investigated in this dissertation.

The first section provides the particular facts about the project and its units. Next, the scope of work for each unit is described followed by a brief description of the process. It is because of these processes that technical problems arise rather than the construction technology or techniques used on this project; therefore, it is felt that an understanding of the different processes is necessary

to gain an appreciation for the design-related problems and their potential relationships. The final section of this chapter discusses the results of the owner's engineering staff's involvement throughout the life of the project. It is included in this chapter because many of the owner's representatives felt that this participation, as well as the different approaches and management techniques utilized on this project, was one of the main reasons that this project was so successful.

3.1 General Characteristics

This study is based on the expansion of a large refinery in the southeast portion of the United States. A brief discussion of the history of the refinery and the project are provided by Alvi.

The refinery was originally built in 1967 to process 100,000 barrels per calendar day (BPCD) of low sulfur crude oil. In the later 1970's, the (owner) decided to expand the refinery to recycle heavy residuum and to increase high sulfur crude running capacity. This expansion increased the refinery capacity to 225,000 BPCD....

Originally, this project was estimated to cost over \$1.1 billion and to take six years (1980-1985) to design and construct. However, the project took less than five years (1980-1984) and cost less than \$900 million. This is over one year ahead of schedule and more than \$200 million under the original budget. (Alvi 1985, 1)

The major participants in this project were the owner, the owner's engineering staff, the design contractor, and the construction contractor. The owner is a large oil corporation. The engineering staff performed some of the design work, coordinated the remaining design effort, and was responsible for coordinating and monitoring progress and quality during the construction phase. (Note: Since the engineering staff represented the owner during the project, the term "owner" will be used for both parties, except when a distinction is necessary to describe specific programs or actions.)

The design contractor was hired under a cost-plus percentage fee to provide engineering and procurement services. The design contractor is a large design firm with a large amount of experience in process design. The design contractor had plenty of available manpower and was already working for the owner on other projects, so that the designer was familiar with owner's systems and procedures.

The construction contractor is a large open-shop contractor experienced in process construction. Under a cost-plus fixed fee (targeted against manhours), the construction contractor was hired

earlier than usual to participate in a constructability program (discussed later) and work with the engineering staff and designer to complete the project as early as possible.

During the project, a design force, which peaked around 1200, provided 3.9 million detailed engineering hours. The construction force peaked at 3700 persons and expended approximately 9.8 million construction manhours.

The project scope included modifying some existing facilities and constructing four major process units plus the supporting offsites. The four major process areas are the Sulfur Block (which will be labeled SRU), the Vacuum Pipe Still Crude Unit (VPS), the Hydrogen Generation Unit (HGU), and the H-Oil Unit. To complete the design in minimum time, the design contractor organized the engineers into four individual design teams -- each one responsible for a different unit. Because of this approach, the project can be analyzed as four smaller individual projects with different design teams under one firm and one construction contractor. Using this approach to study the project will be an advantage since it will reduce the variability introduced by different project

participants on methods of documentation and availability of data commonly found in some studies.

As stated earlier, the project was judged a huge success--it finished a year ahead of the original schedule with a savings of approximately \$200 million. Explanations of this success include (1) the recession climate at the time of construction which provided a large pool of skilled workers and contractors with a reduced workload, and (2) the engineering staff's involvement and initiatives (which will be discussed in Section 3.4).

3.2 Scope of Work

This project consisted of modifications to existing facilities, additions to other facilities, and construction of new facilities. There were challenges in each of these efforts, and a description of each scope of work is provided below.

3.2.1 Sulfur Block

The refinery was originally designed to handle low-sulfur crude. The decision to increase capacity and upgrade the facility to handle high-sulfur crude greatly increased the demand for sulfur treatment. Therefore, the project included expansion of the

entire Sulfur Block. The Sulfur Block is composed of sulfur recovery units (SRU), tail gas treatment units (TGTU) and amine recovery units (ARU). Two SRU's, one TGTU, and one ARU were onsite as part of the original design, so the work on the Sulfur Block consisted of:

1. Installing three SRU's, four TGTU's, and three ARU's
2. Work on common equipment and piperacks
3. Rework on existing units to tie-in the new equipment and modify the equipment to run with a different amine.

Besides the combination revamp/new design, there were three unique characteristics for this block that could impact the number and type of problems. The first characteristic was that this was the only area where the design specifications were prepared by the owner's engineering staff. Secondly, the design work was subcontracted to another design firm due to their familiarity with that process and the owner's requirements. This added another layer of communication and organizational problems. Finally, the procedures for developing the model were different from the other areas. The other models were constructed from the pipe plan drawings and then the isometrics (iso's) were drawn from the model. For

this area, the iso's were drawn from the pipe plan and the model constructed from the iso's. This procedure prevented early design review and increased the cost of changes since piping was being fabricated from the iso's at the same time as the review (O'Leary 1985).

3.2.2 Vacuum Pipe Still #2

A vacuum pipe still (VPS) is one of the main pieces of a refinery. At this facility, there was one VPS. In this project, a new generation of an energy efficient crude unit (VPS-2) which could process 100,000 BPCD was designed and installed. VPS-2 consisted of a higher pressure preflash tower, conventional atmospheric and vacuum towers, heat exchangers for heat recovery, and air preheaters.

The design was done by the design contractor and this unit did not have many problems compared to the other units. Although this was a new generation of VPS, the technology for this unit already existed. Two challenges to the usual design were tight space allocation for the new unit and the larger heat exchanger area (area doubled that of past designs). This led to the use of elevated equipment structures (Aniello 1985).

3.2.3 Hydrogen Generation Unit

Included in this area were the hydrogen generation unit (HGU) and a wastewater treatment plant (WWTP). The HGU was needed to support the H-Oil unit, while the WWTP directly supported the HGU.

The HGU was designed to produce 62.5 million standard cubic feet per day of 98.5% pure hydrogen. The WWTP was designed to treat 32 gpm of "grey water" (water which contains sulfides, cyanide, suspended solids, and ammonia) before discharging the water into the regular waste treatment system. An offsite Air Separation Plant (ASP) supplies oxygen and nitrogen to the HGU (Hunsicker 1985).

The HGU and the WWTP were designed by the design contractor. The ASP was designed and built by another company under a separate contract; therefore, it will not be included in this study. The technology for the HGU was developed by the owner's engineering department so that it was not new to the owner, but it was new for the design contractor. The WWTP was designed using existing technology. The HGU was a step higher in terms of the complexity of the technology, but there were no major design problems on this unit.

3.2.4 H-Oil Unit

The H-Oil Unit converts vacuum residuals to distillable materials. The unit consist of the following sections: "Feed, Reaction, Amine Treating, Catalyst Handling, Fractionation, Light Ends, and Hydrogen Recovery Sections" (Tucker 1985, 1).

This unit was the most technically complex, and more management effort was concentrated here than on the other units. There was no experience with this type of unit among the participants. The design was completed by the design contractor.

3.3 Unit Processes

At the outset of this study, it was believed that the different processes and state of each technology would play a big part in determining the types of problems encountered throughout the project. If this were so, then there would be no correlation between one unit's problems and those of the other units. The opposing view is that the technologies and processes would be different problems for the design teams, but once construction began, the types of problems would not be unique to each unit; rather, they would follow the same pattern. Therefore, it is

useful to study the unique characteristics of each process.

3.3.1 Sulfur Recovery Unit

The Sulfur Block's purpose is to economically recover sulfur for resale as well as to reduce SO_2 emissions to the atmosphere. Sulfur, in the form of H_2S , is produced during the processing of the various feedstocks and is recovered. This is done by introducing a lean amine stream to scrubbers located throughout the plant. The H_2S chemically reacts with the amine and is returned to the ARU where the bond between the two is broken through heating. The amine is then recirculated throughout the plant and the H_2S is sent to the SRU for further processing. The sour gas, as it is known, is fed into the SRU where it is burned under slight pressure (5-10 psig) and converted into sulfur using the Claus reaction. The gases are then passed through three reactors to condense the sulfur gases into liquid sulfur. Using this process, the efficiency of sulfur recovery is 96%. The remaining gases still contain some H_2S that is further treated in the TGTU to bring conversion to 99% efficiency. In the TGTU, a portion of the SO_2 is converted back into H_2S and recycled back to the SRU.

The remainder of the vent gas is burned and dispensed into the atmosphere through a high tower.

3.3.2 Vacuum Pipe Still

The first separation of crude oil is made in a distillation unit. The crude oil is sent to a flash drum where gases are flashed from the liquid. The gases are routed to the atmospheric tower, while the liquid is sent to a furnace where approximately 70% is vaporized. This liquid/gas mixture is sent to the fractionating tower.

Initial separation is made in the tower. Here, the vaporized charge rises inside the tower. The vapor condenses on trays at different heights in the tower depending upon the specific boiling range of the gas. The lighter material continues to rise and the separation made by boiling ranges. The liquid that remains in the bottom of the tower is pumped to another furnace and heated to approximately 750°F, and then pumped to the vacuum tower. The distillation process is the same, except that it is done in a vacuum. The advantage of using a vacuum instead of atmospheric pressure is that the vacuum permits boiling of the crude oil at lower temperatures. For further distillation at atmospheric pressure, it would

be necessary to heat the liquid to 1000°F, where thermal cracking of the crude would occur. The separated distillate streams are then used as feedstocks in other refinery operations.

3.3.3 Hydrogen Generation Unit

Hydrogen generation is produced in a partial oxidation process under high pressure (up to 80 atmospheres). A hydrocarbon feed, oxygen, and steam are preheated and then sent to the combustion chamber which breaks down the feedstock. Hydrogen sulfide and carbon dioxide are then removed from the product gas. The hydrogen gas is used during the hydrocracking process.

The advantage of the partial oxidation process is that it can operate on a wide range of fuels, including those with high-sulfur contents and at high pressure, which reduces the compression costs of supplying hydrogen to the later high-pressure process of hydrocracking.

3.3.4 H-Oil Unit

Cracking refers to the refining process of breaking apart large molecules of hydrocarbons into smaller molecules to increase the yield of hydrocarbons in the gasoline and middle distillate boiling

range. Three general types of cracking are: thermal, catalytic, and hydrocracking. The H-Oil unit utilizes the hydrocracking process and is described below.

The H-Oil Unit uses a high-temperature, high-pressure process to upgrade the vacuum residuals. This process utilizes an "ebullating" bed of catalyst where there is an upward flow of gas and liquid through the small catalyst particles. The ebullating bed permits the onstream removal and replacement of the catalyst to overcome the disadvantage of deactivation of the catalyst.

The feed and hydrogen are preheated and then enter the first reactor where they are mixed with the catalyst. From there, all products enter the second reactor where further reaction takes place. Products are cooled and then distilled in the fractionation tower. Up to approximately 90% of the charge (vacuum residuum) can be converted into distillate material with this process.

3.4 Initiatives

The trend over the past few years has been more owner involvement in all aspects of a construction project. The owners have become more concerned

over the cost as well as the schedule. This has resulted in increased control by owners with the resulting loss of control by contractors. Without debating the pros and cons of this issue, one of the most important benefits of this control has been the ability of the owner to introduce or try different procedures and techniques. These changes would probably not come about, or undoubtedly would be slower in coming, without the insistence or support of the owners.

During this project, the engineering staff worked with the design and construction contractors to try different programs. (Note: This included active use of graduate students from the University of Texas on different research projects. A brief description of the sixteen studies completed is provided in Appendix A.) Below, some of the programs that were successfully initiated are described. These examples include design, construction, and control programs.

3.4.1 Design Programs

Three initiatives that worked well during this project were (1) cut-off dates for preliminary

studies, (2) uniform reviews, and (3) Design Delay Surveys.

Scope problems continue to plague the industry. Part of the problem is that the client often wants to utilize the latest technology and has a tendency to keep making changes throughout the project. To combat this, the engineering staff established cut-off dates for studies to be completed and final design commitments made. Exceptions and extensions were not allowed without upper management approval. This decision helped hold scope changes to a minimum.

The next initiative was joint progress reviews. Instead of separate reviews being done by the client and the design contractor, all involved parties met for the progress reviews. This shortened the review time as well as increased communication among all parties.

The final program that will be discussed is the Design Delay Survey (Como 1983). The survey is similar to Foreman Design Surveys used during construction and tracks the reason for any delays. The survey showed management where delays were occurring, and corrective procedures were undertaken.

The results of this survey increased designer productivity by ensuring that the designer had all necessary information before starting a design so that he could complete his design without stopping and waiting for others to provide more information.

3.4.2 Construction Programs

During construction, two decisions that helped the project finish ahead of schedule were (1) the decision to assemble the VPS unit at ground level, and (2) the decision to implement a constructability program.

Usual practice in erecting a Vacuum Pipe Still is to build the five to six-story unit from the ground up and finish with painting and insulation installation using scaffolding. For this project, the decision was made to assemble the vessels at grade and dress them out through insulation, lifting the almost-finished vessels into place. This saved on scaffolding costs as well as height pay given to craftsmen working on the higher scaffolding.

The second decision was to institute a constructability program. Constructability is based upon "the optimum use of construction knowledge and experience in planning, engineering, procurement, and

field operations to achieve overall project objectives" (Alvi 1985, 11). To accomplish this, the construction contractor assigned qualified people to work in the designer's home office to review the design and make suggestions concerning construction methods throughout the design phase.

Two major constructability efforts were conducted throughout the project (O'Connor 1983 and Glanville 1985). This research resulted in 706 constructability ideas that were evaluated by management. These programs were considered effective, although the actual value of the programs was difficult to measure.

3.4.3 Control Programs

Two control programs used to effectively manage the project were (1) Integrated Schedule and (2) Statistical check of piping drawings.

A Consolidated Management Schedule (CMS) was developed through a joint effort by the engineering staff, design contractor, and the construction contractor. Over 3,000 activities were put on a CPM schedule. With monthly updates and properly-designed reports, each level of management was able to get accurate and timely progress reports. The use of the

integrated schedule shortened the original project schedule by fourteen months, and forced the two contractors to better coordinate their individual activities.

This project had over 42,000 drawings including isometrics (iso's). Previously, the staff would try to check all drawings issued by the designer. Due to time and manpower restrictions, all drawings could not be checked; therefore, a quality control check of piping isometrics was made through random sampling. Selected iso's were routinely checked against P&ID's, the model, etc. to ensure consistency. From these checks, repeated errors were identified and corrective actions taken. The results of this program indicated that piping design improved throughout the project.

3.5 Summary

While Chapter 2 provided a brief background necessary to understand the usual method of completing an industrial project and why a particular sequence occurs, Chapter 3 provided the detailed information concerning the particular project studied in this dissertation. A description of the technical pro-

cesses involved was provided so that a general knowledge of each unit could be used while examining possible relationships of design-related problems later. A section was devoted to the engineering staff's involvement with this project to highlight successful initiatives that were introduced during this project and to establish that this was a successful project where all parties worked well together. This close cooperation does not always exist on a construction project; therefore, the design-related problems detailed in the following chapters could be considered a minimum that would probably be exceeded in other circumstances and projects.

CHAPTER 4

METHODOLOGY

"Construction project success is repeatable" (Ashley, Lurie, and Jaselskis 1987, 69) and various studies are under way to prove that project success can be duplicated. The arguments that construction projects are short-term and each one is unique are still true; however, there are enough similarities in project characteristics and design methods that past projects can and should be studied to learn what was done properly and what needs to be changed. Simply stated, which activities and procedures can be improved before the next project?

Before changing any procedures, a comprehensive study of previous projects must be undertaken. With the advent of the computer, information can be economically stored and retrieved. More firms are utilizing computers for cost and scheduling control. With the proper software, detailed analysis concerning a project can be undertaken.

The main purpose of this study was to extract as much information as possible from the existing data concerning design-related problems, and to judge

whether or not more information could be retrieved from the reports than is currently used. A goal for the study was to analyze the data for trends that could be used in future projects. Since project engineers and managers often complain about the amount of paperwork, it was hoped that with little or no modification, a method could be found so that current reports and procedures can be utilized to help managers make decisions that will avoid future problems--both during a current project and on future projects.

Earlier chapters provided background material on the characteristics of the industry and the specific project. This chapter describes the sources used, introduces the problem categories established for the study, and discusses the statistical methods used to analyze the results.

4.1 Primary Source Documents

Primary source documents are defined by Wiersma (1985, 176) as "original or first-hand accounts of the event." In a project this size, a tremendous amount of information is available for processing and review. Management must decide what

information will be used and in what form that information must be presented. For this study, the primary source documents will be the following reports:

1. Inter-Office Memos (IOM's): This form initiated the correspondence between the field and home offices. These forms were filed by organization of originator and discipline in fourteen three-inch wide ring binders. The number reviewed was over 3000. Since the IOM's are the main source of the data collection, they are discussed in greater detail below.
2. Design Contractor Progress Reports: Progress reports were issued monthly for each unit. They contained a summary of the work accomplished, areas of concern, summary of project control including cost and schedule information, home engineering progress, status of procurement, subcontracts, and construction. Overall progress and manpower curves as well as individual discipline curves were generated which showed planned, previous and current monthly progress.
3. Construction Contractor Progress Reports: Progress reports were issued monthly with updated information on each unit. It contained a narrative section on progress and described scheduled activities for the next thirty days, including any subcontracted activities. The manpower section displayed planned, actual, and forecasted manpower. A separate bar chart was provided for each unit as well as the total project. The bar chart contained the activity, the weighted percentage complete, and scheduled versus actual progress.

4. Engineering Staff Monthly Construction Reports: These reports provided a summary of the construction progress. Significant problems and proposed solutions were highlighted, major accomplishments detailed, and major activities for the next 4 weeks summarized. These reports contained the contract force report including weather, days worked and number of craftsmen present.
5. Engineering Staff Project Weekly Staff Reports: These reports contained an assessment of the project, major accomplishments, major activities planned for the next week, and summarized any major problem areas.
6. Schedules: The schedules were in the form of bar charts which showed design, procurement, drafting, and construction activities.
7. Final Reports: Final project reports were prepared by project engineers for each unit. Information in each report included scope of work, a summary of significant milestones, contractor and vendor performance, problems, and future recommendations.

4.1.1 Limitations of Documentation

In any historical review of a project, the hope is that there will be enough data and that the data are usable. The main problem is that the researcher was not around during the project and could not design the experiment or procedures; therefore, the data might not show exactly what is trying to be proven. As can be observed in the above description of reports available for study, there is an enormous amount of information available. However,

these reports have some limitations including (1) duplication of information, and (2) lack of adequate detail. An example would be the monthly reports, which summarized project and unit status and problems, but did not provide the detail necessary for this study on design-related problems.

4.1.2 Inter-Office Memos

The IOM's are records of the problems that could not be solved in the field without assistance or further clarification from the designer or owner. An IOM was routed through the engineering staff to the design contractor or construction contractor as appropriate. These documents contained the detail necessary to investigate the design-related problems that occurred during the construction phase of this project and are considered the best source of data collection for this study.

The form (see Figure 4.1) showed the unit in question, the discipline which initiated the form, the organization of the originator, the subject of the inquiry, reference to the drawing, specification, etc. in question, description of problem, requested action by whom, date of memo, date answer needed, and response.

INTER-OFFICE MEMO
(TYPE OR WRITE IN BLACK INK)

NO. 79 - 2 - F2188
PAGE 1 of 2

SUBJECT: ADD BEAM @ GAYHER STREET FOR HANGER ROD SUPPT.

REFERENCE: 79-D-202C

1 TO: _____ DATE ISSUED: 11-2-83

FROM: _____ ANS. REQUIRED: _____

DIST: ACTION BY: _____ APPROVAL REQ'D: YES _____ NO _____

MESSAGE: ATTACHED IS SKETCH FSK-216 SHOWING THE ADDITION
OF A STEEL MEMBER FOR HANGER ROD SUPPT.

NOV - 2 1983
NO OFFICE ACTION REQUIRED

DIST: _____ SIGNED: _____

2 TO: _____ DATE ISSUED: _____

FROM: _____ APPROVAL REQ'D: YES _____ NO _____

DIST: ACTION BY: _____ PROCEED AS ABOVE: YES _____ NO _____

COMMENT: _____

DIST: _____ SIGNED: _____

3 TO: _____ DATE ISSUED: _____

FROM: _____ APPROVAL REQ'D: YES _____ NO _____

DIST: ACTION BY: _____ PROCEED AS ABOVE: YES _____ NO _____

COMMENT: _____

DIST: _____ SIGNED: _____

Figure 4.1 Example of Inter-Office Memo

The information from the IOM's that was used in this study included:

1. type of problem
2. date of origination
3. unit involved
4. discipline involved
5. organization of originator

This information was entered into a database and analyzed using various statistical techniques.

Limitations found in the IOM's were that (1) there was no mention of the economic or schedule impact from these problems and (2) not all forms were complete--the response blocks were often blank. Conclusions drawn from the IOM's are therefore made in general terms and not with the accuracy usually associated with objective data.

4.2 Secondary Source Documents

Secondary source documents are "reports or accounts of events that are at least once removed from the event or experience" (Wiersma 1985, 176). In this study, secondary sources include Project Significant Items List (SIL) and reports (including several dissertations and theses) generated by students at the University of Texas throughout the life of this project (see Appendix A).

4.2.1 Significant Items List

The SIL was started by student researchers on this project and discussed by Smith (1983, chap 3). The SIL is a summary of the project's normal activities and problems from conception to completion. It was divided into two sections: the first section summarizes the progress of major activities taking place and the second section lists the problems which might cause cost/schedule estimates to be exceeded.

The list was compiled throughout the entire project; however, analysis was only done on that portion of the project that was completed when engineering design reached 60% completion. This means that the study concentrated on the engineering phase of the project. Since the SIL was developed throughout the life of the project and tried to assess potential problems, results were not available as to the accuracy of the identification of problems and the actual impact it had on the project. The questions that then arise from reviewing this list are:

1. Is there a way to investigate if the problems identified in the SIL actually arose?
2. What was the solution proposed to solve the problem?
3. What was the actual impact on the schedule or cost?

The answers to these questions had to be found in the documents relating to the construction phase. A survey of these reports showed that there was no direct way to determine the actual problems or assess their impacts.

Even though actual economic results could not be found for the SIL, it does achieve its objectives and can be valuable for use in further projects for the following reasons:

1. Problem categories for the design phase of a project are proposed.
2. The SIL summarizes the events and conditions recognized by upper management as potential problems.
3. The SIL demonstrates that certain problems occur during a specific period in the project and can be explained. This infers that these problems could be repeated in another project.
4. The SIL alerts management to potential problems on the project by summarizing the various reports. Although the information is available in other reports, the summary often calls attention to common problems that may be missed while reviewing numerous reports.

Could the SIL be used for the purposes of this study? The first objective in this study is to identify the types and magnitude of design-related problems that occur during the construction phase of a

project. The problems identified in the SIL are too general for analyzing the design-related problems that occurred during the construction phase. It must be remembered that the problems in the SIL originated from progress reports, etc. that had a limitation of being too general for detailed study; therefore, the SIL will have the same limitation.

The third objective of this study is to find an early predictor of future problems. The process of compiling the SIL precludes its use as an early predictor. The list is compiled from progress reports that usually lag actual time by one month. After compilation, the list is circulated to management for review and comment before final printing. This can take an additional month, meaning that the SIL lags actual project progress by approximately two months. Also, the SIL is too general for use in the construction phase of the project.

4.3 Problem Categories

In order to study the types of problems that arise in the construction phase of a project, a hierarchy of problem categories must be established. There are various accepted categories of problems used

in the construction industry, but these vary according to their intended use. For example, the classification of problems used during litigation for claims differ from those used in Smith's study (1983, 34) of potential problems that occurred in the engineering phase of this project.

Smith developed categories that covered problems typically encountered during the design phase of an industrial project (see Table 4.1). However, it quickly became obvious that the problems encountered during the construction phase of a project are different than the problems encountered during the design phase. The activities, objectives and major participants in each phase differ; therefore, the problems should not be expected to fall into the same categories.

Table 4.1--Problem Categories by Smith

-
- | | |
|-----|--|
| 1. | Lack of Scope Definition |
| 2. | Client Decision Delay |
| 3. | Undefined Authority and Responsibility |
| 4. | Unrealistic Schedule |
| 5. | Underestimated Costs |
| 6. | Licensor Agreement Delays |
| 7. | Design Delays |
| 8. | Procurement Delays |
| 9. | Engineering and Construction Contractor
Conflicts |
| 10. | Permit Delays |
| 11. | Design Difficulties |
| 12. | Procurement Difficulties |
| 13. | Strict Specifications |
-

Source: Smith, 34.

Other research concentrating in the area of project risk has also attempted to categorize the problems that are encountered in a project. Due to the topic, this research is concerned with problems throughout the project's life and spans the entire spectrum of a project's life cycle. The categories used in an unpublished study by Kehoe (1986) are shown in Table 4.2. These categories were refined from an initial study by Bliudzius and Ashley (1985, 26) and are shown in Table 4.3.

Table 4.2--Problem Categories by Kehoe

-
-
1. Design
 2. Planning/Scheduling
 3. Plans/Specifications
 4. Contracts/Documents
 5. Cost/Money
 6. Materials
 7. Engineered Equipment
 8. Construction Equipment
 9. Environmental
 10. Management
 11. Workers/Labor
 12. Safety
 13. External Factors/Agencies
-

Source: Kehoe

Table 4.3--Problem Categories by Bliudzius and Ashley

-
-
1. Documents
 2. Environment
 3. Equipment
 4. Materials
 5. Monetary
 6. People
 7. Project's Characteristics
-

Source: Bliudzius and Ashley, 26.

From the research on project risk, a very important concept concerning the classification of problems has emerged. The concept is the hierarchy of problem categories. Care must be taken to organize the categories so that all categories are on the same level and not actually a subarea of a category. An

example of this would be trying to compare the number of interference problems to the number of specification problems. The problem with this comparison is that interference problems are not in an exclusive category, but are actually a subarea of drawing problems. The researcher must be careful to compare the drawing category to the specifications category to make proper conclusions.

The above categories were an excellent start for this study; however, there was no single system that totally captured the detail believed necessary to complete this study. Therefore, after review of the existing categories and an initial classification of IOM's, eight categories have been chosen. Table 4.4 lists and defines the categories used. All categories have various subareas, but due to the brief description of the problems given in the IOM's, the subareas would be almost impossible to identify. The classification into subareas is considered "soft" since they could vary considerably according to the people performing the classification. However, the classification of problems into the various categories does not appear to pose that difficulty and could probably be duplicated by other investigators. Therefore, sub-

areas for some categories are provided that may prove enlightening for detailed study of individual categories, but this study mostly concentrates on the analysis of problem categories.

Table 4.4--Problem Categories for Design-Related Problems

DRAWINGS

Classification when questions or problems arose related to a drawing.

- Interference
- Discrepancy
- Omissions
- Error

SCHEDULE

Problems that could affect the schedule. Used when delays are encountered because of missing information or drawings. This category was also used when information was provided by the design contractor to clarify or request information.

- Information needed
- Information provided
- Drawing needed
- Drawing hold

DESIGN

Category used when changes to the original design resulted in engineering rework or when the memo identified design deficiencies.

- Error
- Change

Table 4.4--Continued**SCOPE**

Defines the work to be accomplished.

- Additional work

PROCUREMENT

Category used to cover vendor problems, material problems, or requests for field purchase.

- Engineered equipment
- Commodities
- Field purchases
- Vendor problems
- Fabrication

SPECIFICATIONS

Category used when there was a question concerning the specification, a request for a material substitution or the correctness of a particular specification.

- Clarification
- Incorrect
- Change (i.e. Material Substitution)

CONSTRUCTION

Category used to classify problems that were caused by the construction contractor. These problems were not caused by the design team, but solutions to these problems were provided by the design team.

- Error
- Problems

QUALITY ASSURANCE/QUALITY CONTROL (QA/QC)

Category used when problems were identified that pertained to quality. It was expected that this category would be relatively small. Quality problems usually refer to the quality of material or the workmanship involved as required in the specifications. The quality control system should deal with these problems. Since these are usually not design-related problems, the IOM's would not reflect quality problems.

4.4 Measuring Instruments

Once problems are identified and classified, the second and third objectives of this study can be accomplished. The second objective is to examine the data for specific relationships and trends, while the third objective is to carry these relationships further and determine methods to predict potential problems before they impact the project.

If predictors can be found, then feedback loops can be established so that the design can benefit from the information discovered during construction. A short-term feedback loop could be established during ongoing projects to avoid potential problems or mitigate the effects of current problems by utilizing the information from problems in the early stages of construction.

A long-term feedback loop could be established to track the results from completed projects and build a database which designers could use to prevent problems from recurring on future projects of similar design.

To accomplish these objectives, statistical analyses on the database were done. The following tests were used: time series analysis, contingency

tables, and regression analysis. Due to the differences in some of the underlying assumptions made for some of these tests, it is beneficial to discuss each test; however, detailed discussion, derivation, and procedures used to run these tests can be found in most statistics books and will not be reiterated herein.

4.4.1 Time Series Analysis

Time series analysis is a statistical technique which analyzes observations over a specified period of time. These observations are made at equal time intervals--daily, weekly, monthly, etc. and are dependent upon the previous observations. This is different from most techniques that assume independence between variables.

Time series analysis can be useful in forecasting, if a model based on historical data can be developed. Models have been successfully developed for forecasting economic trends or optimizing control functions. Examples are predicting the price of a corporate stock or adjusting input to control output in a chemical process.

Very little historical data, particularly recorded in detail over a long period of time, is

available in the construction industry. Since the IOM's can be separated into monthly intervals of date of origination, an effort was made to develop a time series model which would be useful for forecasting future problems. If successful, it could be used to predict problems at the end of the project using the problems identified at the beginning of the project. A model could also be developed to predict problems that could occur on similar, future projects. (Note: More research would be needed to verify the results.)

The time series models of interest for this study are the autoregressive integrated moving average processes, known as ARIMA models. A complete and detailed description of this method can be found in texts such as Time Series Analysis Forecasting and Control by Box and Jenkins or Applied Time Series and Box-Jenkins Models by Vandaele. However, to introduce the reader to this procedure, a brief description of the method is provided below.

As the name implies, there are three terms that explain the model. Autoregressive models express the value of the dependent variable as an aggregate of the previous values and a random value known as a disturbance or shock. Moving average models express

the dependent variable in terms of a finite number of previous values multiplied by weighting coefficients for each term. The weighted coefficients can be positive or negative, and do not have to equal unity when summed. Integrated refers to the process of differencing between the terms. Differencing is the mathematical process of subtracting the successive terms from the preceeding term in the series. Differencing is used to convert a nonstationary series into a series that exhibits stationarity. Stationary models are identified by three characteristics: a constant mean, a constant variance, and the correlations are the same. Nonstationary series are missing at least one of the above characteristics.

Steps to identify the model include:

1. Calculate the autocorrelations and partial autocorrelations.
2. Run regression equation on significant terms.
3. Use estimates from regression equation.
4. Run regression equation using significant terms and residuals.
5. Sweep out insignificant terms using the t-distribution and test model.

Successful development of a model would show that the data from one project worked, and time series

analysis could be used. This would have to be validated with other projects before acceptance.

4.4.2 Contingency Tables

Contingency tables test the data for independence between two variables by using a chi-square distribution (χ^2). The chi-square distribution is a family of curves that are non-symmetrical and dependent upon the degrees of freedom in the data. The null hypothesis to be tested states that the two variables are independent. The alternative hypothesis then becomes the statement that the two variables are not independent and there is a relationship between the two variables.

The test is run by listing all possible combinations of the two variables as shown in Table 4.5. In the table, N represents the sample population. The two variables X and Y have observed frequencies of A, B, \dots, I . The marginals are the sum of a row or column, such as $A+B+C$. From these marginals, the expected frequencies for each cell are calculated based on the assumption that the two variables are independent. If they are independent, then the same fraction of variable Y must hold true for each combination with variable X . The calculation

for independence is the sum of squared difference between the observed frequency and the expected frequency. If the calculated χ^2 is greater than critical χ^2 from a statistical table, then the null hypothesis that the two variables are independent fails, and a conclusion that the variables are not independent can be reached.

Table 4.5--Example of Contingency Table

A	B	C	A+B+C
D	E	F	D+E+F
G	H	I	G+H+I
A+D+G	B+E+H	C+F+I	N

4.4.3 Regression Analysis

Regression analysis is a statistical technique used to show the relationship between two or more variables. A mathematical relationship is developed to predict a variable, known as the dependent variable, from one or more variables, known as independent variables.

Simple regression predicts the relationship between one dependent variable and one independent

variable. Multiple regression involves a dependent variable and two or more independent variables. Linear regression implies that the relationship is a straight line, while curvilinear regression involves the development of equations that define an appropriate curve. Therefore, simple linear regression analysis develops the equation of a line to explain how the dependent variable is related to the independent variable. The general equation is

$$y = a + bx$$

where y = dependent variable
 x = independent variable
 a = y-axis intercept
 b = slope of the line

To determine the estimates for a and b , the method of least squares is used. The strength of the regression relationship is established by the coefficient of determination, which is symbolized by R^2 . It measures on a scale from 0 to 1 the strength of the relationship, with 1 implying a very strong relationship.

Once the regression equation is developed, it must be tested for: (1) strength of regression relationship, (2) statistical significance, and (3) whether a coefficient can be equal to zero.

Statistical significance is tested through the F-test. The hypothesis states that the coefficient b is equal to zero. If the hypothesis is not true, then there is a statistically significant relationship and the regression equation can be used.

The t-test is similar to the F-test. It tests the same null hypothesis: the coefficient equals zero. Either test can be used in regression models when there is only one independent variable. However, the F-test must be used when there is more than one independent variable to test the model's significance, while the t-test is used to test if a particular coefficient of an independent variable is zero.

The purpose of regression analysis is to use the developed equation to predict a value for the dependent variable given the independent variable. When predicting a value, it is obvious that the actual value of a variable will not be exactly equal to the estimated value. Therefore, an interval in which the actual value is expected to fall is usually calculated. The width of the interval is determined by the confidence level that the user specifies--in most cases, the desired confidence level is 90 or 95%.

When using regression analysis, it must be remembered that a relationship between two variables is established, but it does not explain a cause-effect relationship. It only shows the strength of a relationship. Determination of cause-effect must be done by the analyst. Care must also be taken to stay within the bounds of the data. The accuracy of the regression is within the limits of the existing data and, without analysis, it cannot be proven that the regression will still be accurate with data outside the completed study. Therefore, extrapolation beyond existing bounds must be done with caution.

CHAPTER 5

PRESENTATION OF RESULTS

As stated earlier, each unit was designed by a separate team and constructed using a phased approach. Figure 5.1 displays the design schedules and the construction schedules for each unit in this project.

The IOM's contained data allowing problems from each unit to be categorized by organization of originator (will be labeled organization), discipline of originator (discipline), or problem category. This study concentrates on the construction phase of an industrial project; therefore, it was necessary to identify documents generated during the construction phase. To determine when the IOM's were generated, the design schedule, the construction schedule and the cumulative number of problems for each unit are combined in Figures 5.2 thru 5.5. These figures show that the IOM's originated in the construction phase of the project and illustrate the fast-tracked approach used on this project. Table 5.1 summarizes the percentage of design completed when construction began.

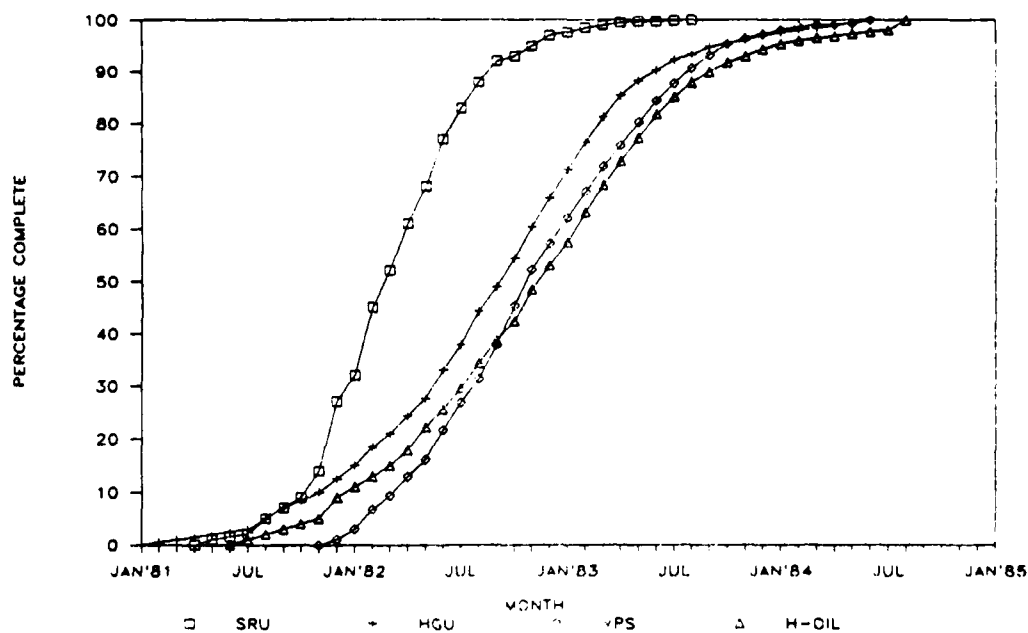


Figure 5.1a Unit Schedules--Design

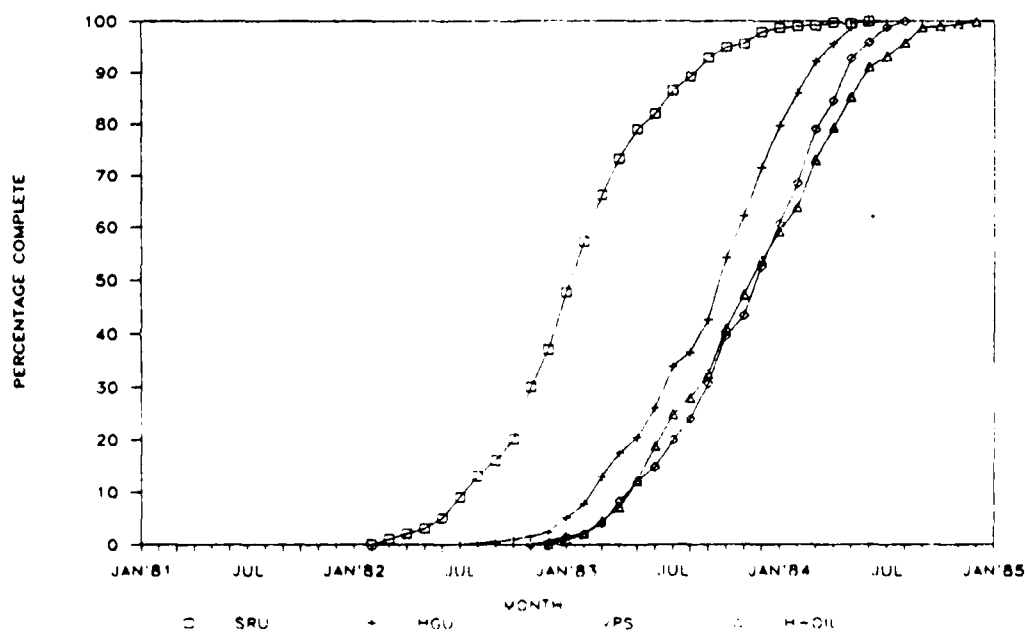


Figure 5.1b Unit Schedules--Construction



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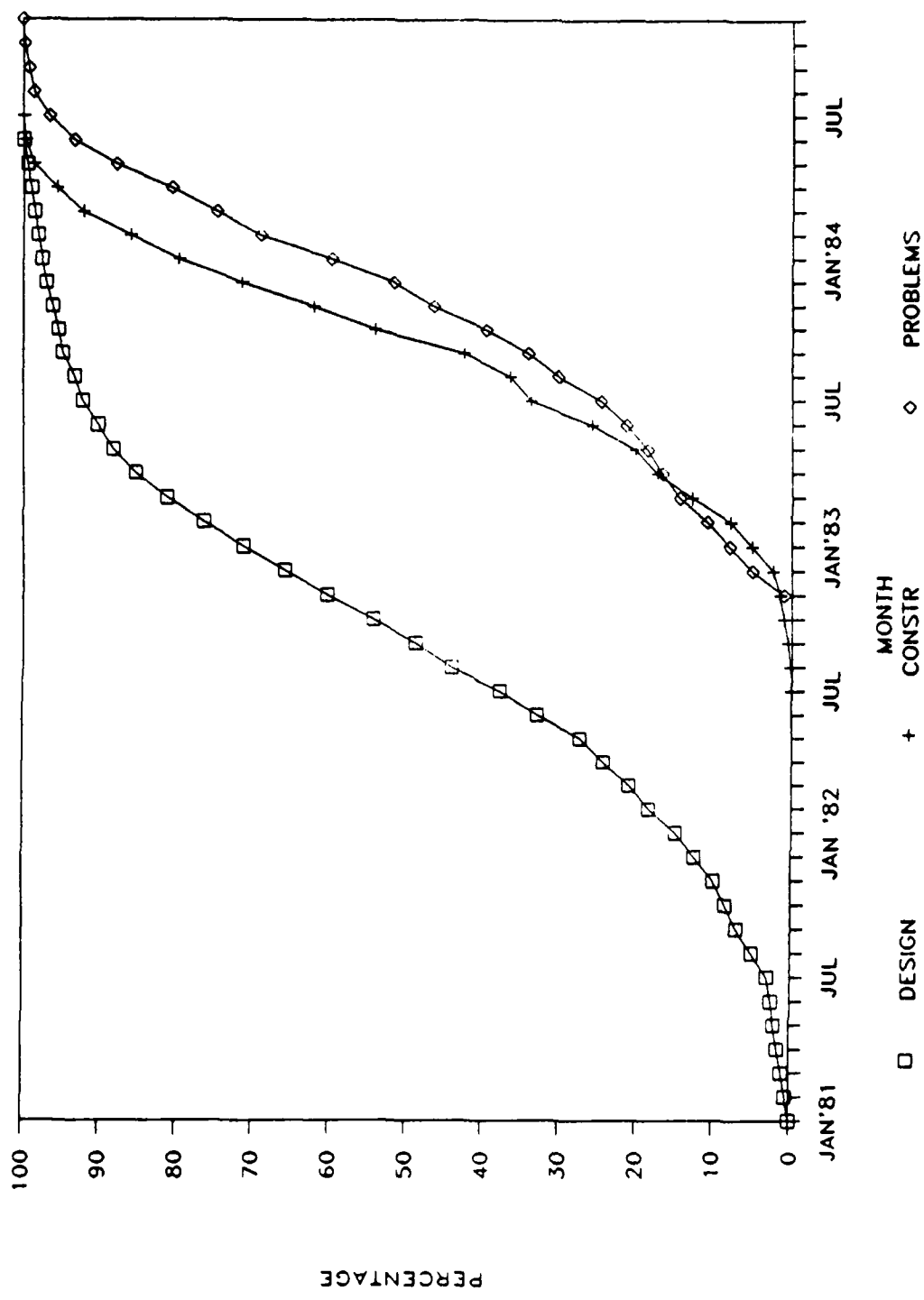


Figure 5.3 HGU--Schedules and Problems

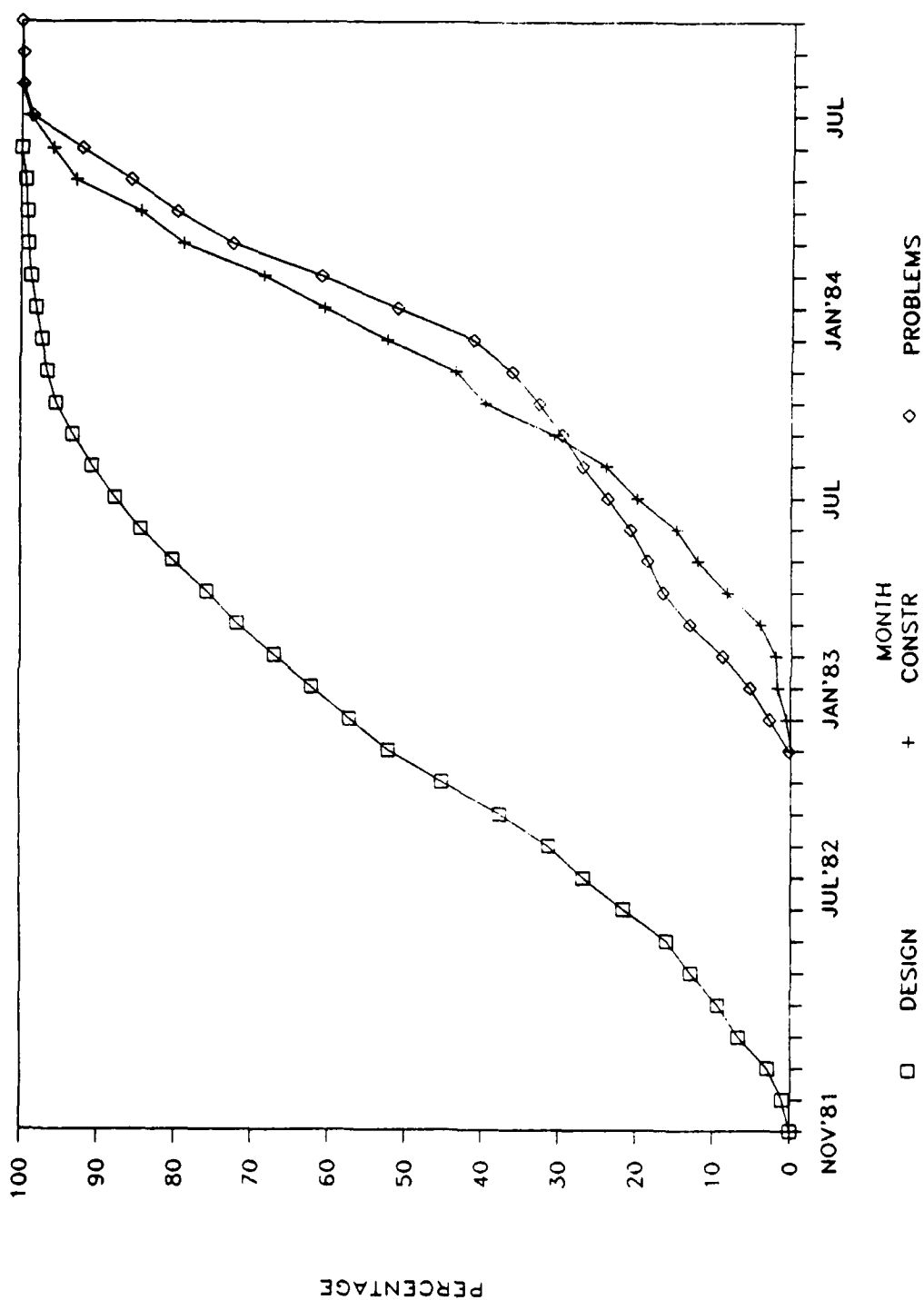


Figure 5.4 VPS--Schedules and Problems

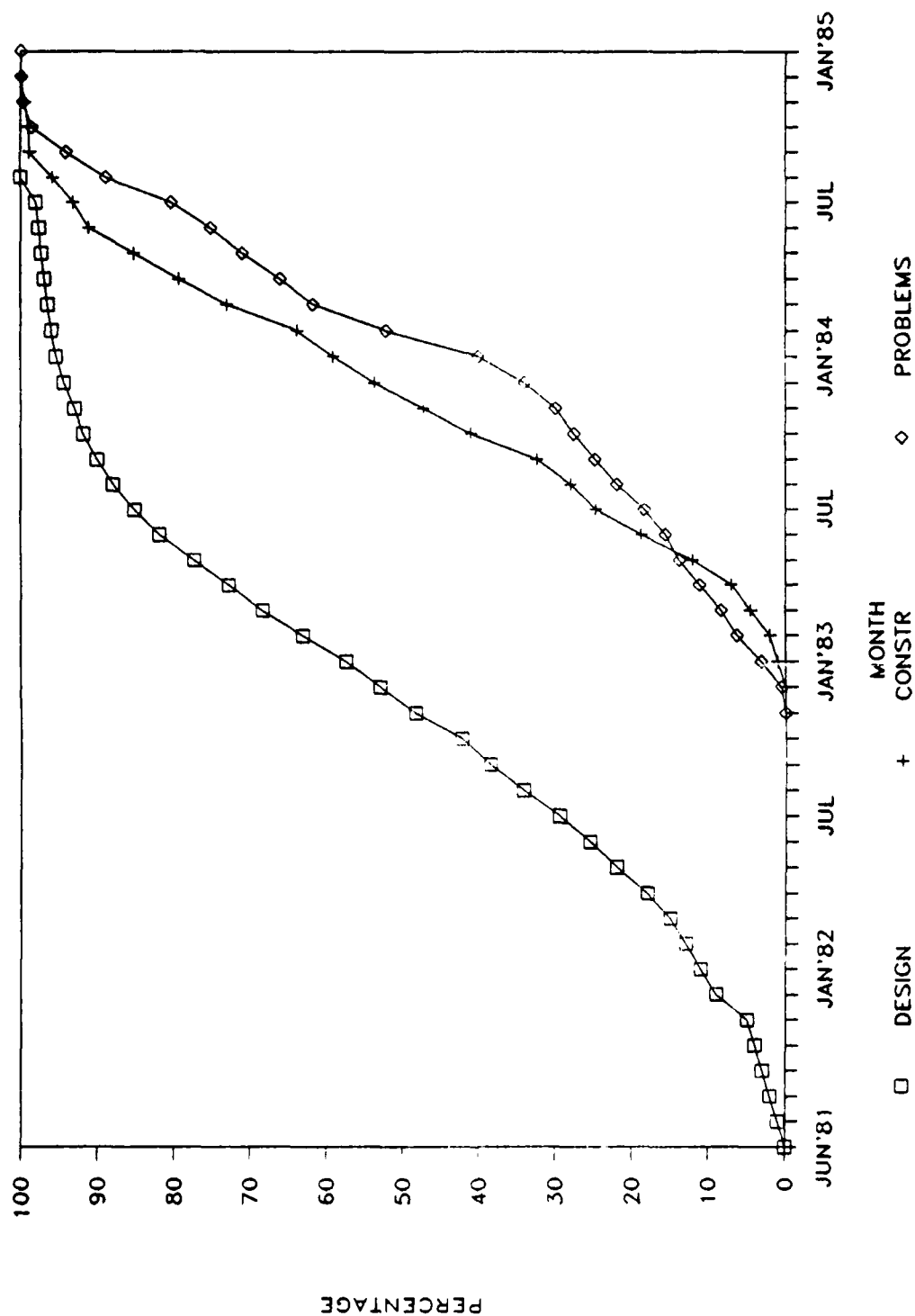


Figure 5.5 H-Oil--Schedules and Problems

Table 5.1--Percentage of Design Complete When
Construction Began

Unit	Date of Construction Start	% Design Complete
SRU	Jan, 82	45
HGU	Jul, 82	57
VPS	Nov, 82	44
H-OIL	Dec, 82	48

5.1 Timing of Problems

At the outset of this study, some of the critical questions that had to be answered concerned the type of design problems that would arise for each unit, and whether management could react quickly enough to prevent repetition of the same problem on the subsequent units. The engineering staff felt that if there was a recognized problem on the first unit (in this case, the SRU) that management would take action to prevent its recurrence. The answer to this question was very important since management action to prevent recurrence of a problem would eliminate any chance of using the problems of one unit to predict the number and types of problems of another unit. Each unit would have different problems that would

dominate the construction phase as the project progressed.

Two important factors that initially would affect the results were the communication between all concerned parties working on the project and the schedule of each unit. This project was designed by independent teams of engineers under the guidance of the owner's staff in conjunction with the construction contractor, who was assisting in the constructability process. It was obvious that many channels of communication existed and, with the complex issues to be solved, accurate and quick communication would be a challenge. However, one of the studies completed earlier by the University of Texas (Greenwood 1982) dealt with the communication issue. Results of this study identified several barriers to effective communication as well as draw attention to the communication process. Therefore, due to subsequent management action, it is thought that effective communication existed on this project.

The second factor to be investigated centered around the schedule and the timing of design, construction, and the discovery of design-related problems. The previous figures as well as construction

schedules for each unit provide information to answer the question:

Is there enough time in the project to discover a problem on one unit and take corrective action to prevent a recurrence on another unit?

The SRU was designed and constructed first and led the other units by as much as nine months. However, the designs of the other units were in-progress and the design by each discipline was completed before the actual construction of that particular activity was completed on the SRU. An example would be: the civil design of the VPS was completed around June, 1982, while the civil construction of the SRU was completed around November, 1982, a lag of five months. Therefore, a particular problem probably did not reach the home office in time to change the design of the following units.

The implication is that, in a fast-tracked project, it is feasible for similar problems to be repeated in design although the construction crew and field office would be aware of them. Using this reasoning, the analysis of the IOM's continued by looking for similarities and differences among the units. Among the factors investigated were organization of originators, disciplines, and problem types.

5.2 Total Problems

The total number of problems identified in the IOM's are shown in Table 5.2. The results are not very surprising -- the most technically complex unit had the largest number of problems, while the lowest number of problems were recorded in the unit (VPS) which has the best known technology (see the Total Problems column). It should be noted that communication between the home offices and the field using the IOM's was started when the SRU was 30% complete. Therefore, it is believed that there actually were more problems than shown here for the SRU. This will be discussed in more detail later.

Table 5.2--Comparison of Total Problems and Manhours per Unit

Unit	Total Problems (Prob)	Total Direct Labor Manhours (DLM)	Prob/DLM (#/10,000 DLM)
H-OIL	893	2,137,000	4.2
HGU	675	1,137,000	5.9
SRU*	506	1,326,000	3.8
VPS	405	1,323,000	3.1

* The SRU was 30% complete when the IOM's were begun

Just looking at these numbers can be misleading. The large number of problems on the H-Oil unit could lead someone to conclude that it was the worst unit constructed. That is not actually the case. To avoid a misleading conclusion by reviewing only one piece of information, direct labor manhours are added to the table. It can be seen that the H-Oil unit had 60% more manhours than the SRU which was second. Therefore, more problems could be expected from the H-Oil unit.

Column three is the ratio of Problems/DLM. This number represents the average number of problems that occurred on each unit for each 10,000 hours of direct labor. Using this ratio, the lower the number, the better the project. Table 5.2 shows that the VPS had the best Prob/DLM ratio, while the HGU had the worst. The H-Oil was higher than the SRU, but due to the implementation date of the IOM's, it is believed that not all SRU problems were recorded. Therefore, the SRU ratio would probably be higher than the H-Oil. This demonstrates that although the H-Oil had the largest number of problems, proportionally, the H-Oil unit was well-managed, designed, and constructed.

Figures 5.6a and b show the cumulative number of problems and the percentage of problems versus the percentage construction complete. The abscissa was changed from calendar months because each unit had a different duration, and using the percentage construction complete makes comparison among the units more accurate. All units display the same characteristic as the projects evolve. They all follow a reverse-S curve where more problems are identified in the beginning and the end of the project than in the middle. This is opposite of what one might expect since progress usually follows an S-curve where progress starts slowly, peaks in the middle, and slows down at the end. This implies that all units had trouble at the beginning of the project and immediately before or during start-up operations. Figure 5.6b shows that all units not only follow the same trend, but the range in percentage of problems versus the percentage of construction complete is rather narrow--not varying more than 10% between the highest and lowest values.

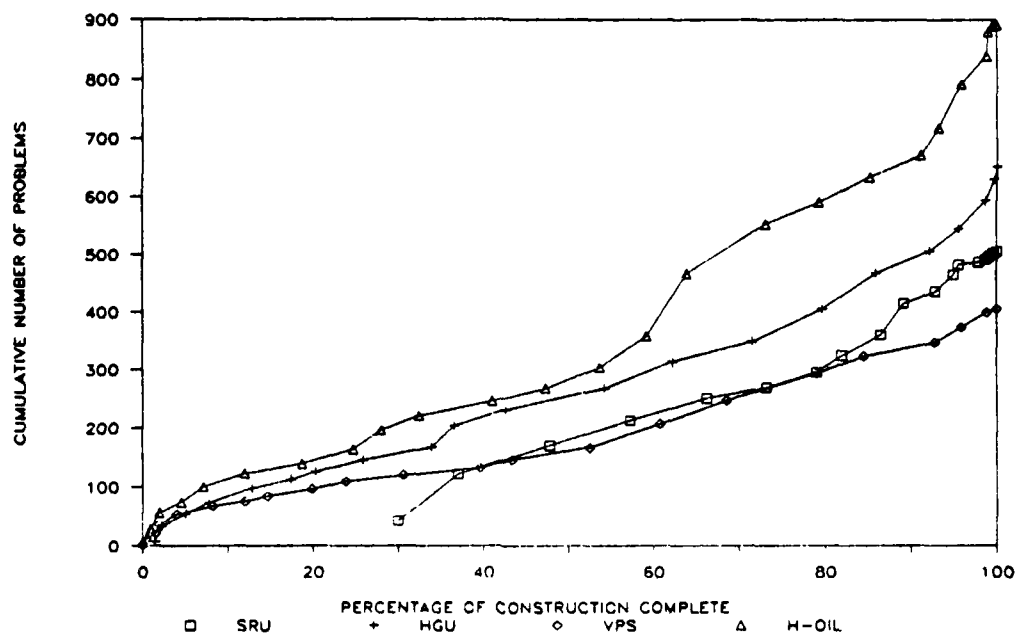


Figure 5.6a Total Problems--Cumulative

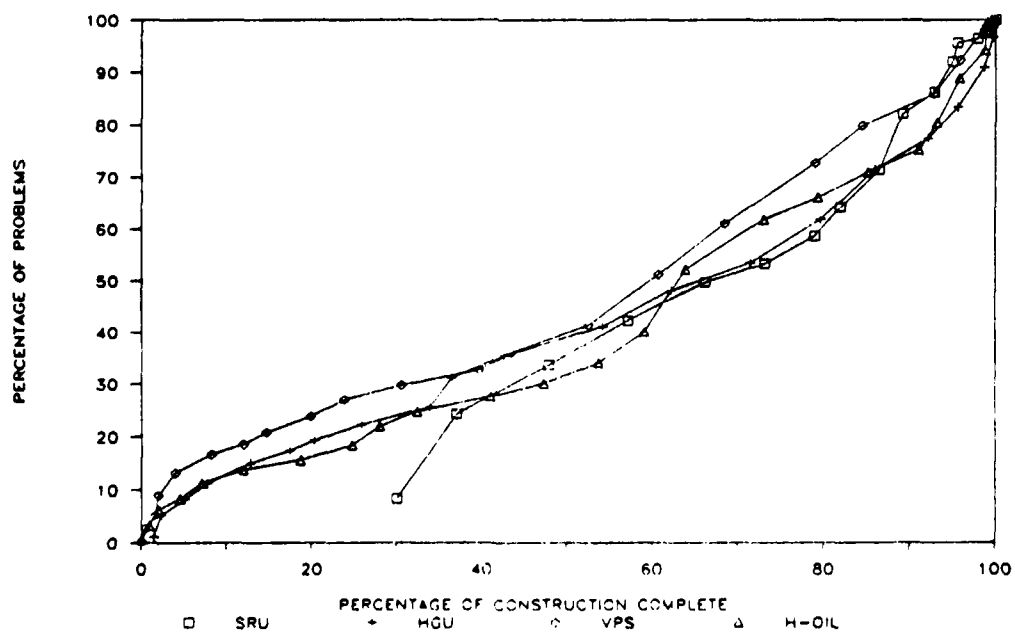


Figure 5.6b Total Problems--Percentage

5.3 Classification by Problem Category

The IOM's relayed problems from the field back to the home office and were concerned with design-related issues and how to expeditiously solve them. Once the categories were developed, the problems for all units were classified according to the Process Units and the eight categories shown in Table 4.4. The results are shown in Table 5.3.

This initial classification showed consistent trends. The top four categories for each unit are:

SRU	Drawings, Design, Schedule, and Procurement
HGU	Drawings, Schedule, Design, and Scope
VPS	Drawings, Schedule, Specifications, and Scope
H-OIL	Drawings, Schedule, Design, and Scope

As can be seen above, Drawings was the number one category of problems. Schedule, Design and Scope were the other critical categories.

A few other preliminary observations demonstrate the accuracy of the memos for recreating what happened during the project and the fact that problems were repeating throughout the different units. The SRU's scope of work consisted of adding

	NUMBER OF PROBLEMS				TOTAL	PERCENTAGE OF PROBLEMS				
	SRU	HGU	VPS	H-OIL		SRU	HGU	VPS	H-OIL	TOTAL
DRAWINGS	167	179	91	246	683	33.0	26.5	22.5	27.5	27.6
SCHEDULE	85	123	67	179	454	16.8	18.2	16.5	20.1	18.3
DESIGN	92	118	54	163	427	18.2	17.5	13.3	18.3	17.2
SCOPE	36	103	57	134	330	7.1	15.3	14.1	15.0	13.3
PROCUREMENT	60	56	28	67	211	11.9	8.3	6.9	7.5	8.5
SPECIFICATIONS	26	46	60	32	164	5.1	6.8	14.8	3.6	6.6
CONSTRUCTION	37	43	36	69	185	7.3	6.4	8.9	7.7	7.5
QA/QC	3	7	12	3	25	0.6	1.0	3.0	0.3	1.0
TOTAL	506	675	405	893	2479	100.0	100.0	100.0	100.0	100.0

Table 5.3--Problems Classified by Problem Category

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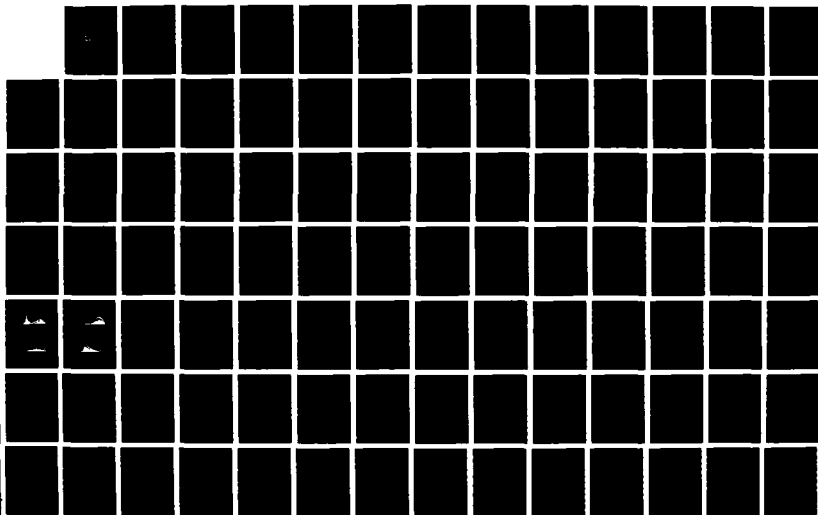
ANALYSIS OF DESIGN-RELATED PROBLEMS FROM AN INDUSTRIAL
PROJECT(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB
OH J R GLAVAN MAY 88 AFIT/CI/NR-88-122

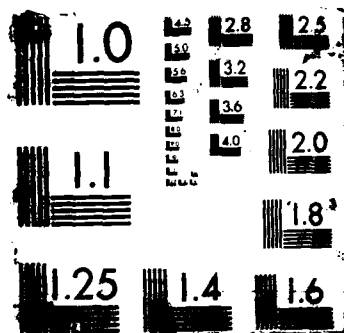
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units with known processes; therefore, it is not unexpected that scope problems would not be ranked higher (it was sixth out of eight). Given that the VPS had the most common technology and the least number of problems, the high number of specification problems was unexpected. Further investigation showed that 51/60 specification problems were in the instrumentation area and 48 of these problems were identified by the construction contractor. Although the Specifications category was not one of the four highest-ranking categories throughout the entire project, it is interesting to note that the instrumentation discipline accounted for approximately 85% of the specification problems (exception: H-OIL at 69%) and the construction contractor identified approximately 80% of these problems.

Figures 5.7 thru 5.13 present the cumulative number and percentage of problems for each problem category, except QA/QC which did not have a high percentage for any of the units. Overall, trends show that the most complex unit, the H-OIL, had the largest number of problems in all categories except the Specifications category; however, it does not dominate when compared on a percentage basis.

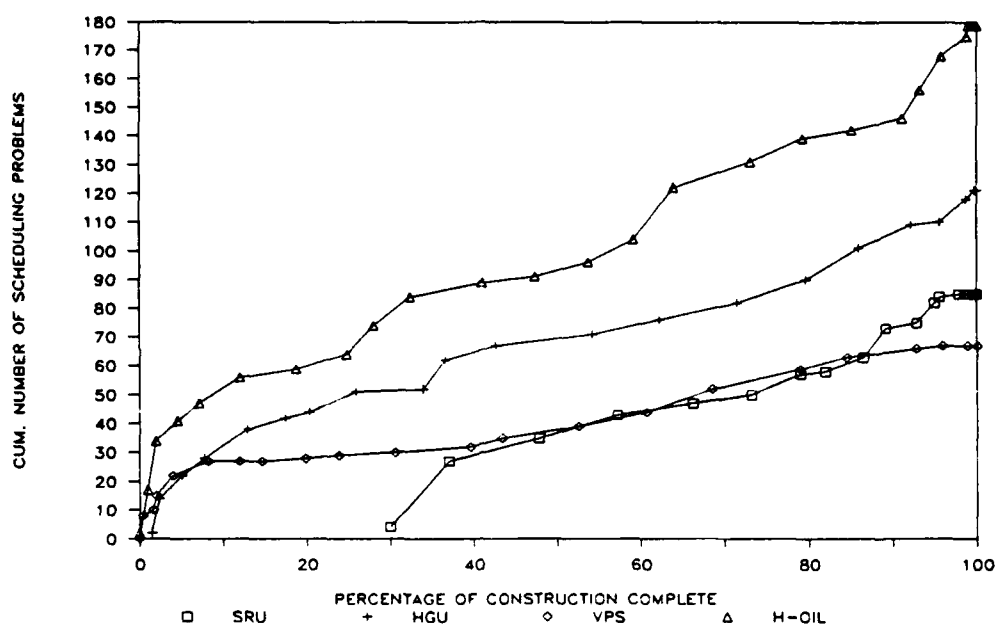


Figure 5.8a Schedule Problems--Cumulative

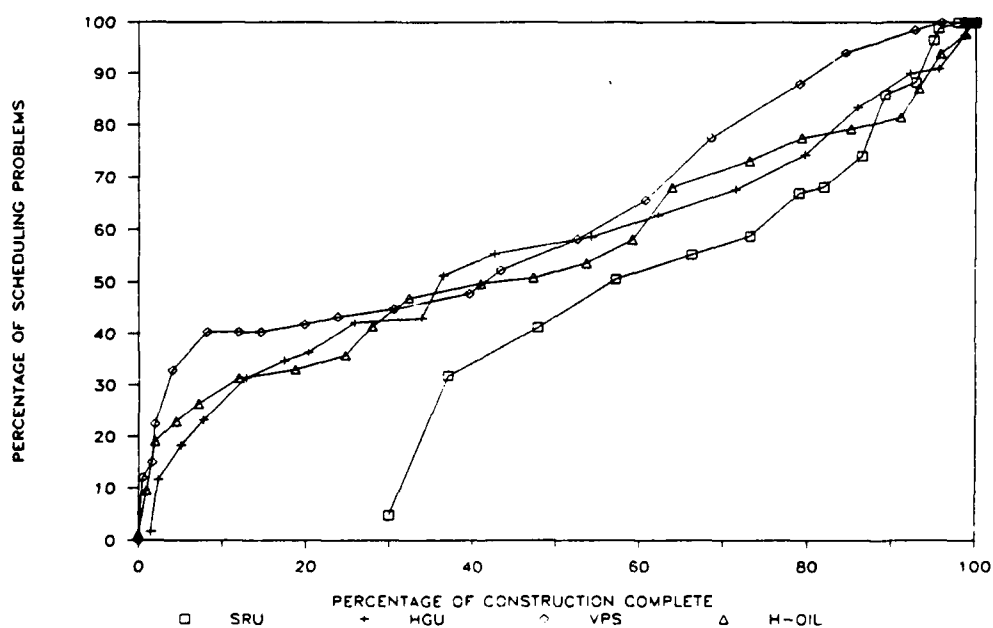


Figure 5.8b Schedule Problems--Percentage

Figure 5.7 shows the Drawings category. The trend is linear. This indicates that drawing problems can be found throughout the project and are not associated with any particular discipline.

Schedule problems are shown in Figure 5.8. Most scheduling problems occur at the beginning for each unit. Approximately 35% of the scheduling problems occur within the first 20% of the project. This graph implies that some scheduling problems had occurred in the SRU project that were not covered in the memos.

Figure 5.9 shows the Design problems. Design problems vary widely until the end of the project, where approximately 40% of the design problems occur over the last 20% of the project. This shows that design problems are not always found until the end of construction when the unit is being prepared for start-up.

Figure 5.10 Scope has a definite trend--it increases exponentially as the project nears completion. Again, 50-60% of scope changes occurred in the last 20% of the project. This probably occurs as the conceptual design is actually realized with construction being completed, and modifications and changes

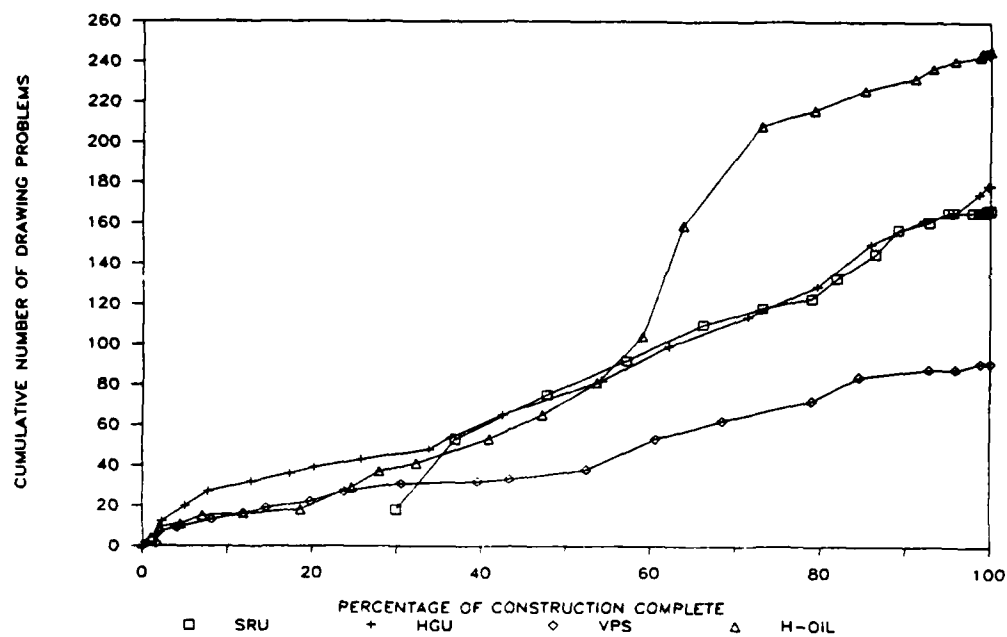


Figure 5.7a Drawing Problems--Cumulative

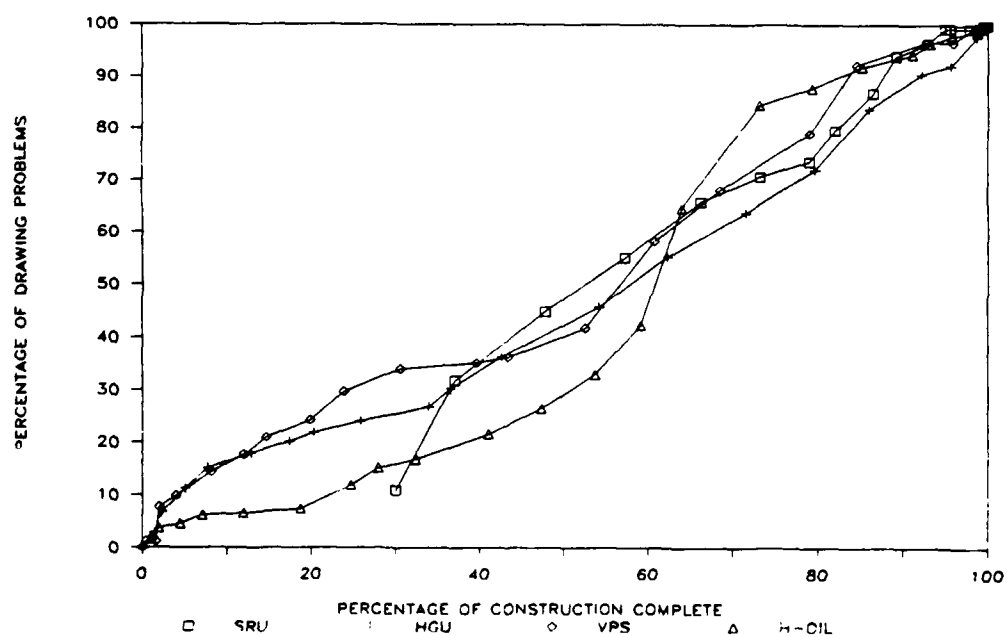


Figure 5.7b Drawing Problems--Percentage

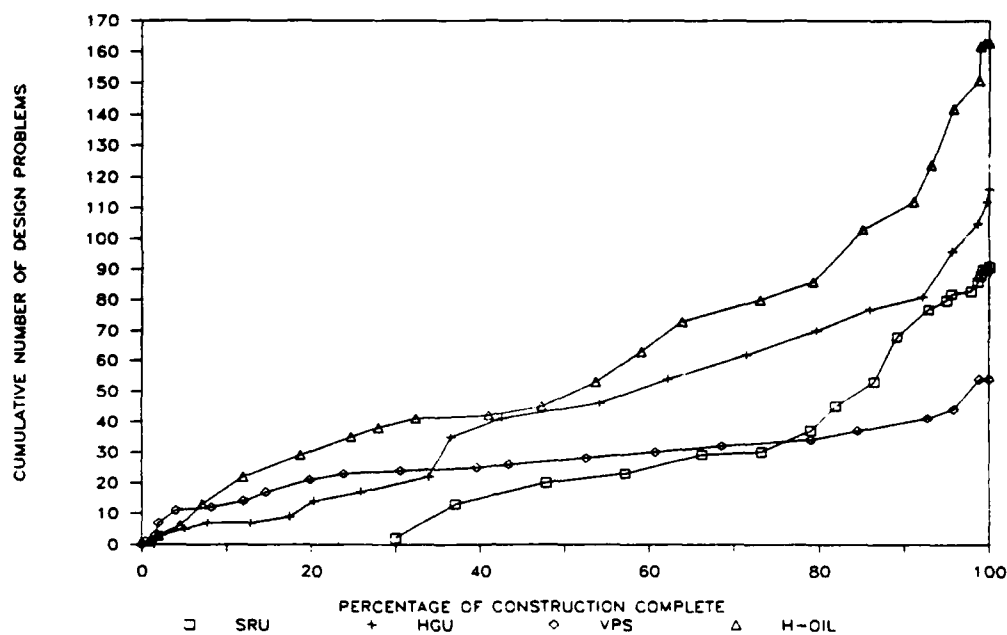


Figure 5.9a Design Problems--Cumulative

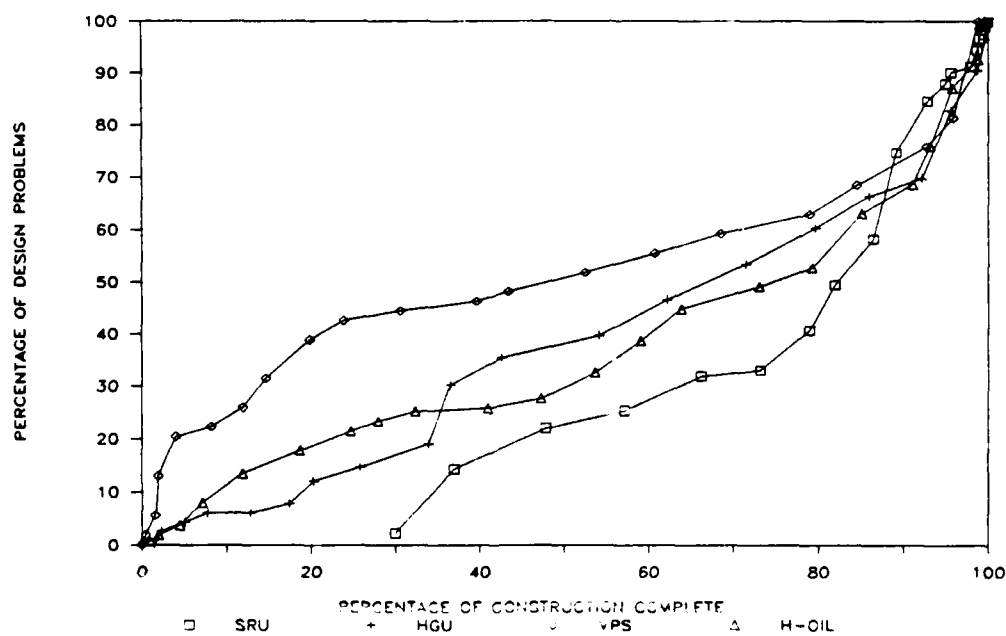


Figure 5.9b Design Problems--Percentage

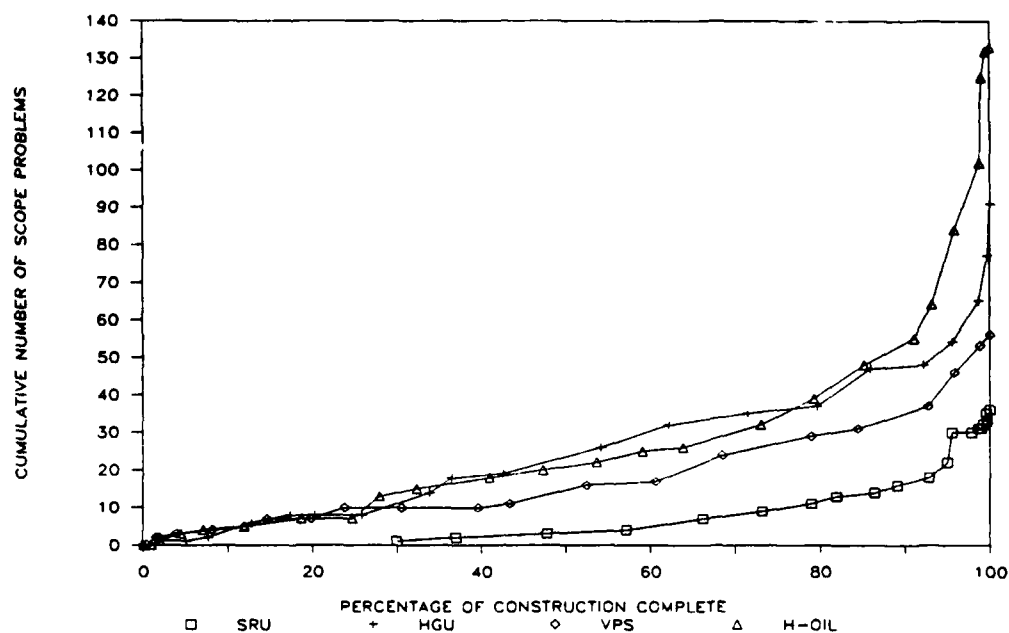


Figure 5.10a Scope Problems--Cumulative

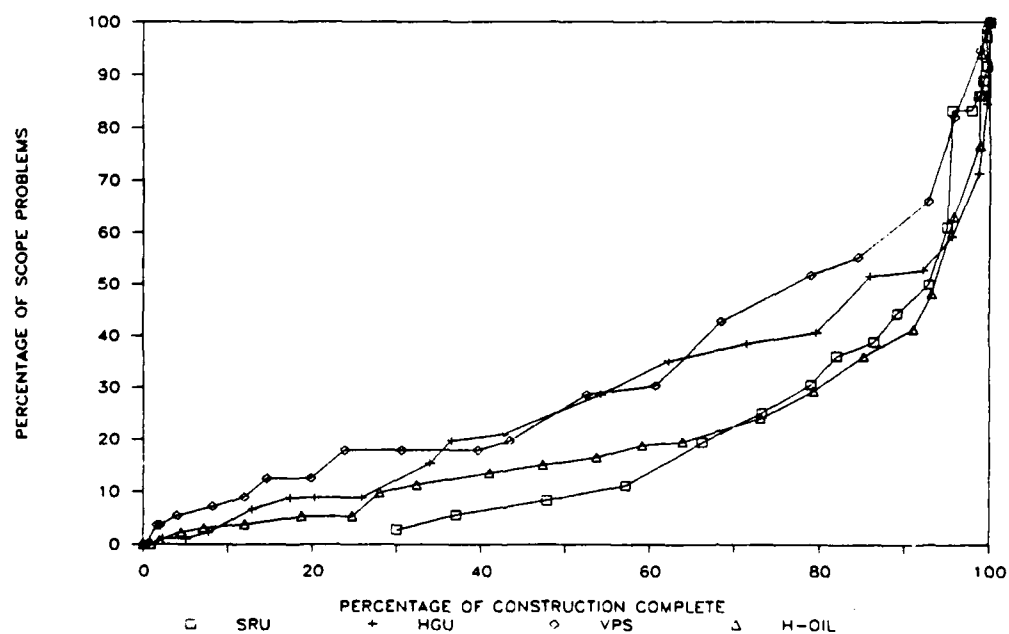


Figure 5.10b Scope Problems--Percentage

are needed to complete the units as actually envisioned.

It should be noted that Scope changes were minimized throughout the project by management (see discussion in Chapter 3.4.1) and judging by the results of this graph, management was quite successful with this effort until the end of the project. At the end of the project, the hectic pace of testing and start-up probably led to a change in management decision-making that allowed some changes to be approved without strict review.

Construction problems (Figure 5.11) occurred throughout construction, but 35% of the problems occurred within the first 20% of the project. This should not be unexpected due to separate contractors handling design and construction--the constructor is not familiar with the design contractor's methods. Initially, construction errors have to be checked with the design team to determine the problem solution. Later in the project, there is not as much flexibility for change, and errors must be corrected to comply with the drawings and specifications. In this situation, there will be construction rework without correspondance to the design office. These mistakes

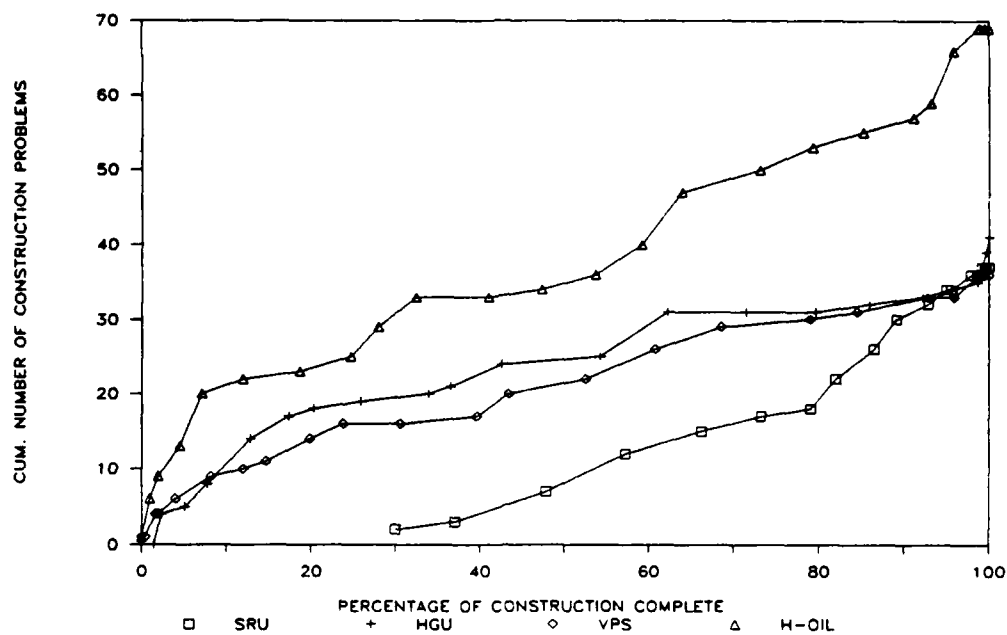


Figure 5.11a Construction Problems--Cumulative

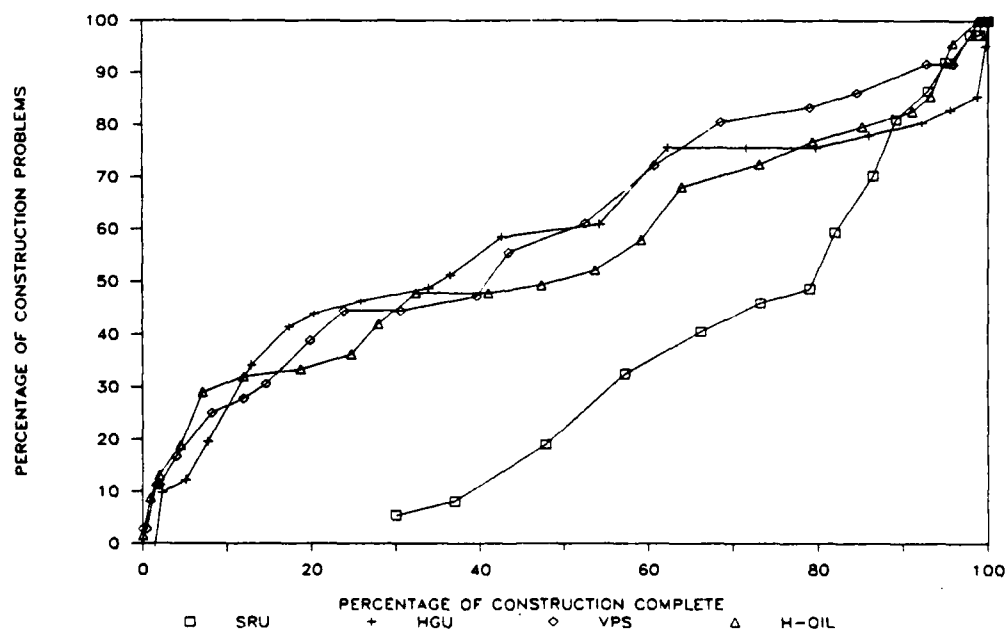


Figure 5.11b Construction Problems--Percentage

will probably be picked up by the QC system and not through the IOM's.

Figure 5.12 shows the Specifications category, which exhibits the same characteristics for all four units, since all four units had the same construction schedule and were heavily influenced by the instrumentation group. Results from this category have been previously discussed.

Procurement problems are shown in Figure 5.13. Purchase orders are usually processed early in the project, and delivery of the ordered equipment and commodities takes place when needed throughout the project. Therefore, very few problems should occur during the initial phase of construction--this is confirmed by the graphs. Procurement problems can occur (1) throughout the project when items are not supplied on time, and (2) at the end of the project when the equipment does not operate as expected or specified. In this project, 50% of procurement problems occurred in the last 20% of the project indicating that equipment was not operating properly and vendor problems had to be solved to successfully complete the project.

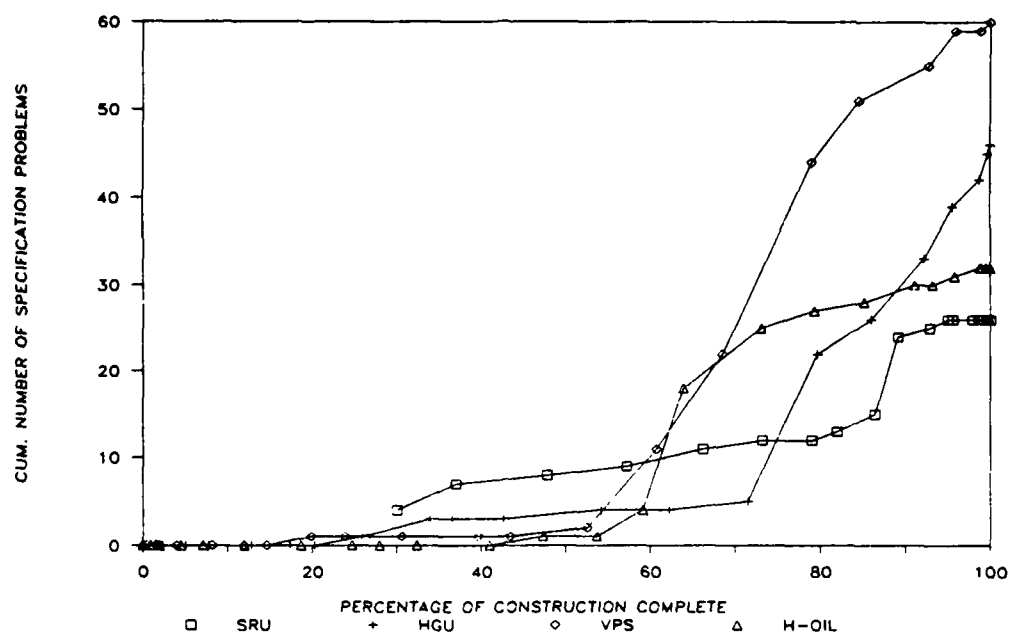


Figure 5.12a Specification Problems--Cumulative

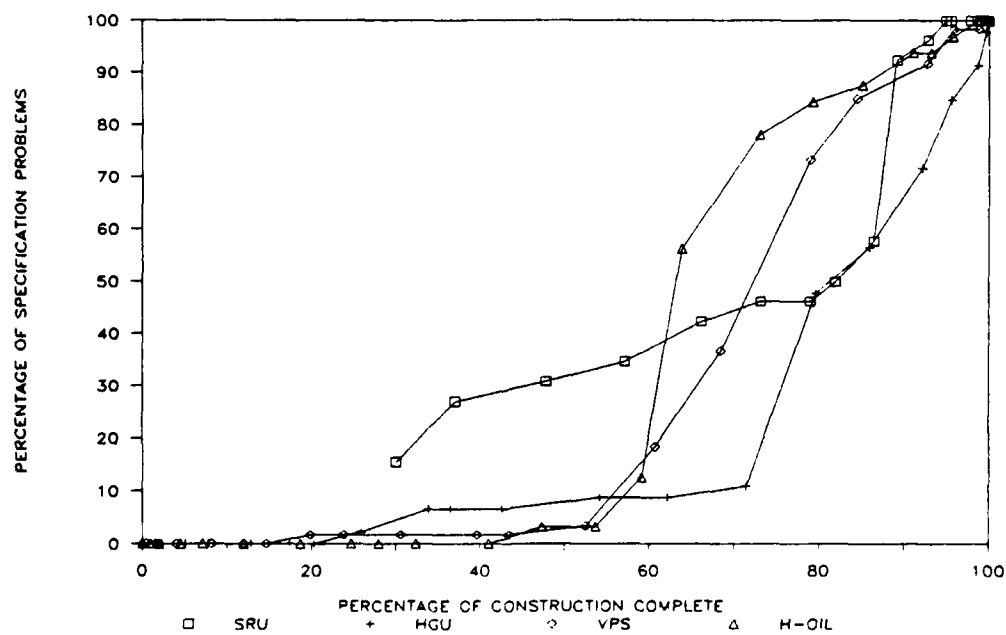


Figure 5.12b Specification Problems--Percentage

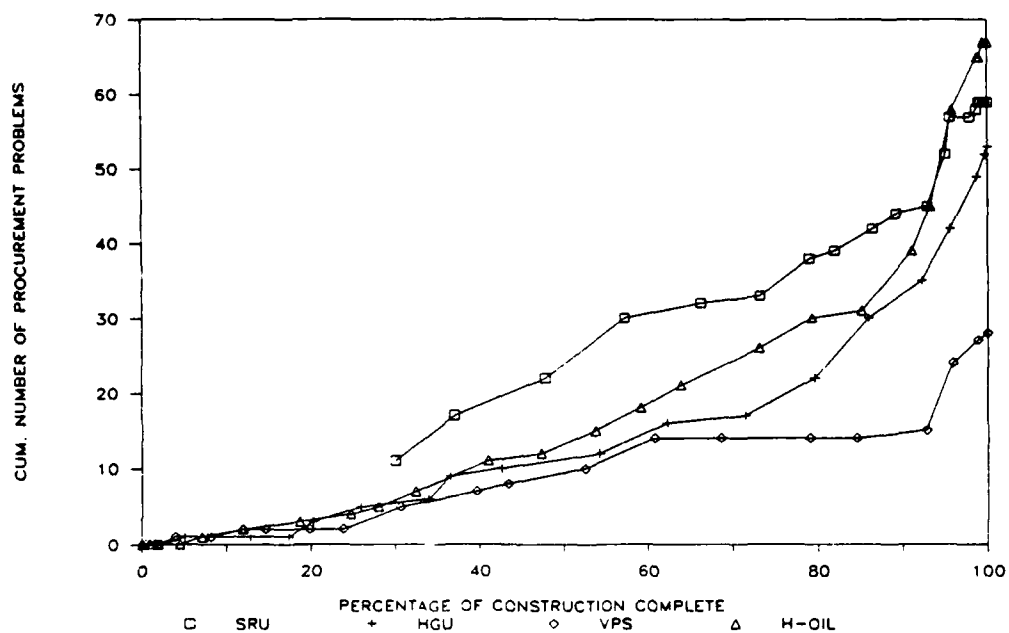


Figure 5.13a Procurement Problems--Cumulative

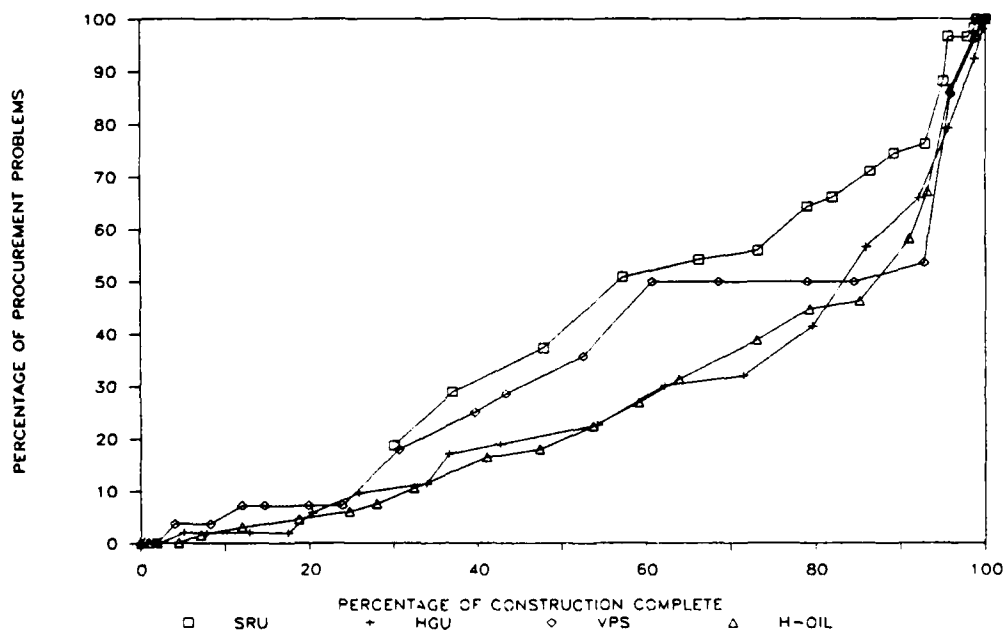


Figure 5.13b Procurement Problems--Percentage

More detailed analysis was undertaken in the following sections because these graphs showed consistent trends throughout all units. The problems have been examined in terms of organization and discipline of originator.

5.4 Classification by Organization

The problems have been investigated to determine:

1. Which organization originates the IOM's?
2. Does a particular organization dominate a particular phase of the project?
3. Are certain problem categories significantly dominated by one organization?

The construction contractor should be expected to originate most of the IOM's since the project is under construction at this time, and many problems are not identified until construction activities commence. The owner should not be originating too many memos since most of his correspondence should be addressed to the designer. The design contractor should be somewhere below the construction contractor in number of memos originated. The results are tabulated in Table 5.4.

As expected, the owner originated very few of

NUMBER OF PROBLEMS				PERCENTAGE OF PROBLEMS				
OWNER	DESIGN CONTRACTOR	CONSTRUCTION CONTRACTOR	TOTAL	OWNER	DESIGN CONTRACTOR	CONSTRUCTION CONTRACTOR	TOTAL	
SRU	69	149	288	506	13.6	29.4	57.0	100.0
HGU	89	310	276	675	13.2	45.9	40.9	100.0
VPS	33	201	171	405	8.2	49.6	42.2	100.0
H-OIL	48	507	338	893	5.4	56.8	37.8	100.0
TOTAL	239	1167	1073	2479	10	47	43	100.0

Table 5.4--Problems Classified by Organization

the memos (approximately 10% except for the H-OIL unit where the owner originated 5%). Surprisingly, the design contractor originated more memos for all units except the SRU, which followed the expected results. It is felt that the SRU differed from the other three units because it was the first unit to begin construction, and the construction crew generated more memos for this unit to clarify initial project conditions and learn the designer and owner's system. The crews were able to learn which problems actually needed a response from the home offices. The explanation of the design contractor having a higher percentage than the construction contractor could not be explained without answering question three--Are certain problem categories significantly dominated by one organization?

The second question is answered by examining Figures 5.14 thru 5.16 which show the cumulative number of problems and the percentage of problems originated by each organization versus the percentage of construction complete. Figure 5.14 shows that the majority of problems originated by the owner occurred after 80% project completion for all units except the

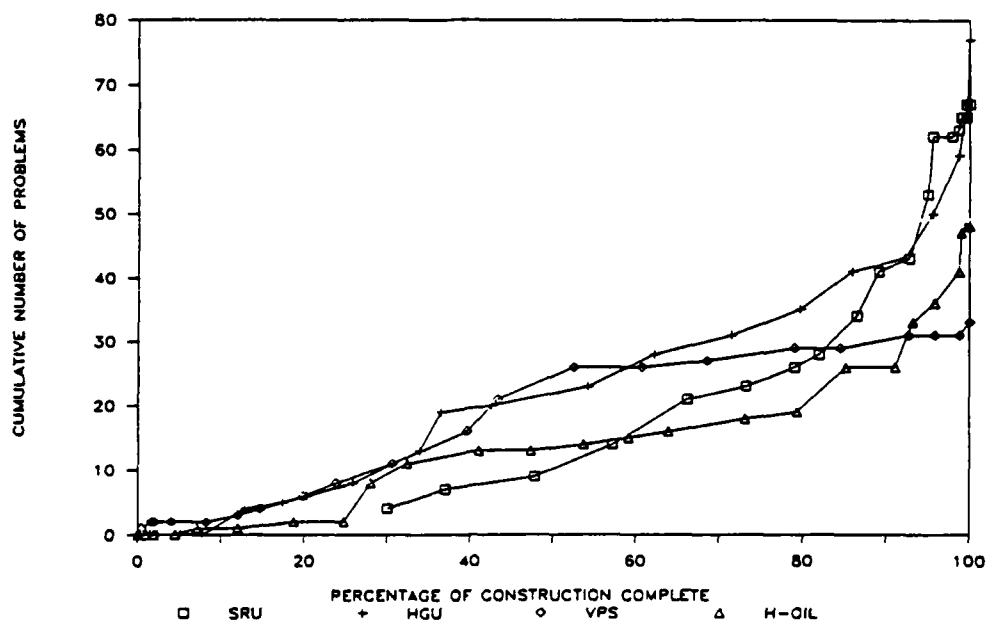


Figure 5.14a Owner-Originated Problems--
Cumulative

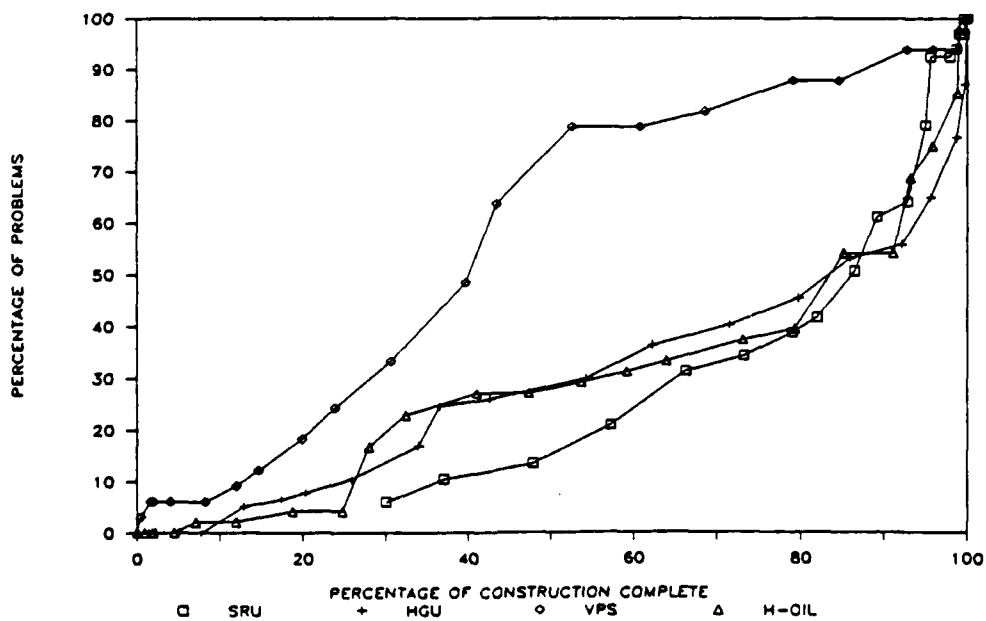


Figure 5.14b Owner-Originated Problems--
Percentage

VPS. This implies that the owner found more problems near the close of construction or the beginning of start-up. The VPS could be an exception due to its known technology and fairly straight-forward design.

Figure 5.15 shows that the problems identified by the constructor roughly followed the S-curve typically depicting construction progress. The majority of problems were identified during the period of peak activity in the field.

Figure 5.16 shows when problems were identified by the designer. In all units except the SRU, a reverse-S curve is present. This implies that the designer had to generate more memos (1) in the beginning of the project to provide information or to clarify design instructions and (2) at the end of the project to modify the design or change the scope of the design to ensure that the unit would operate as desired. It can be observed that in the last 20% of the construction period, 40% of the memos originated by the design contractor occurred.

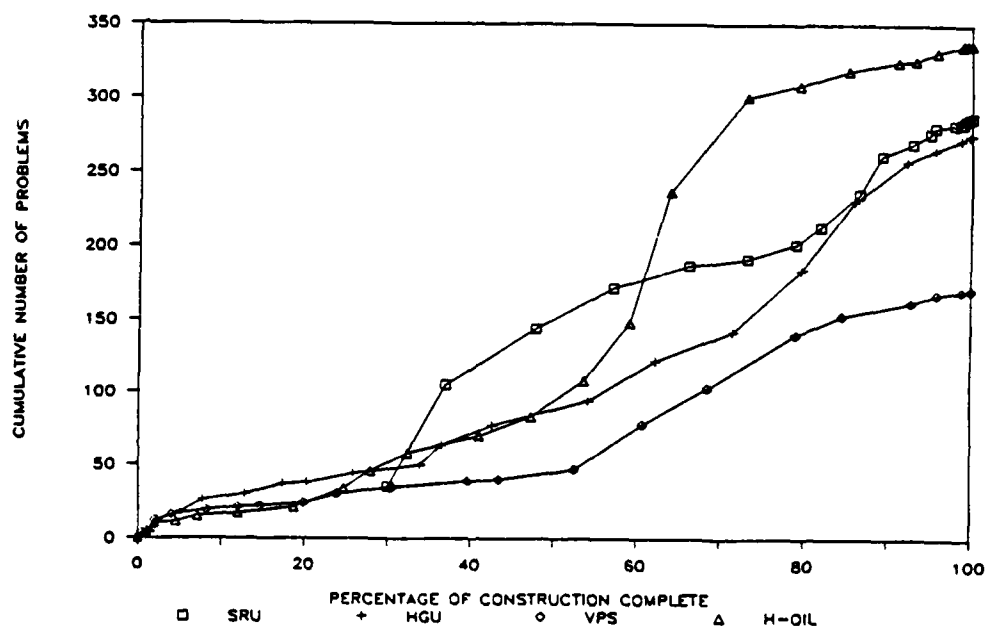


Figure 5.15a Construction Contractor-Originated Problems--Cumulative

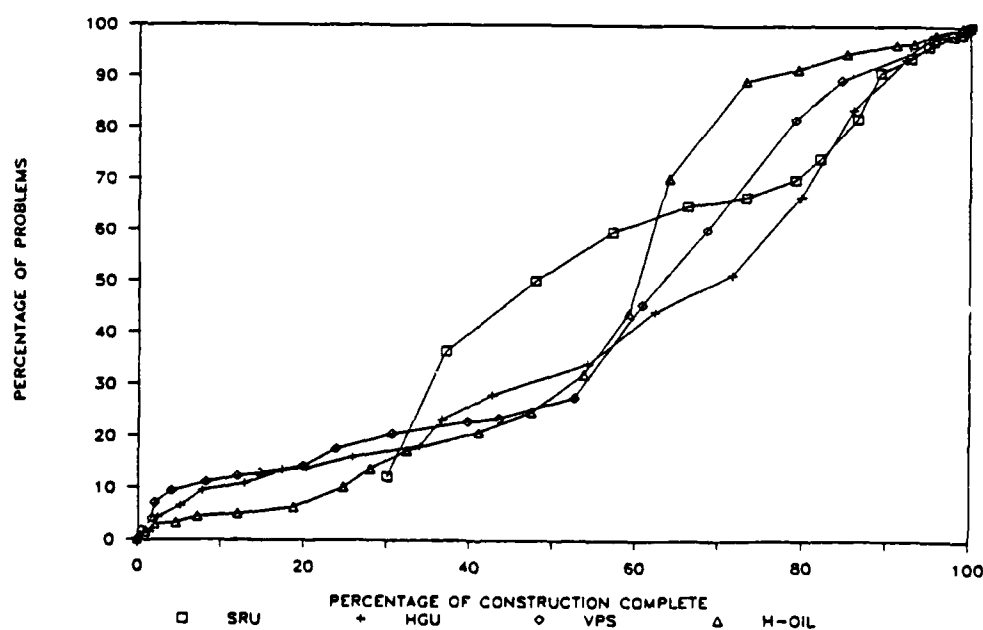


Figure 5.15b Construction Contractor-Originated Problems--Percentage

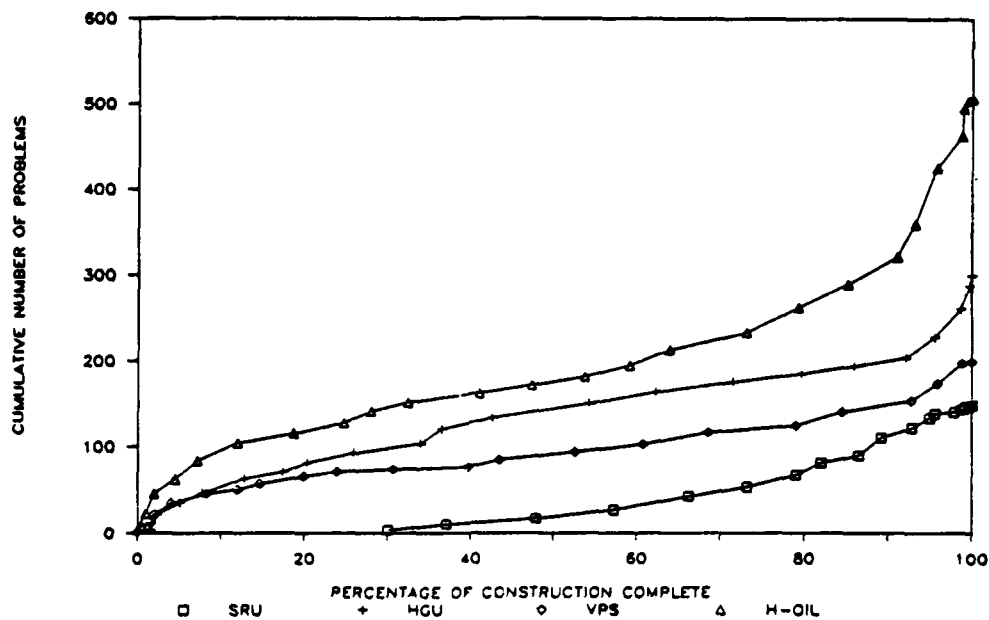


Figure 5.16a Design Contractor-Originated Problems--Cumulative

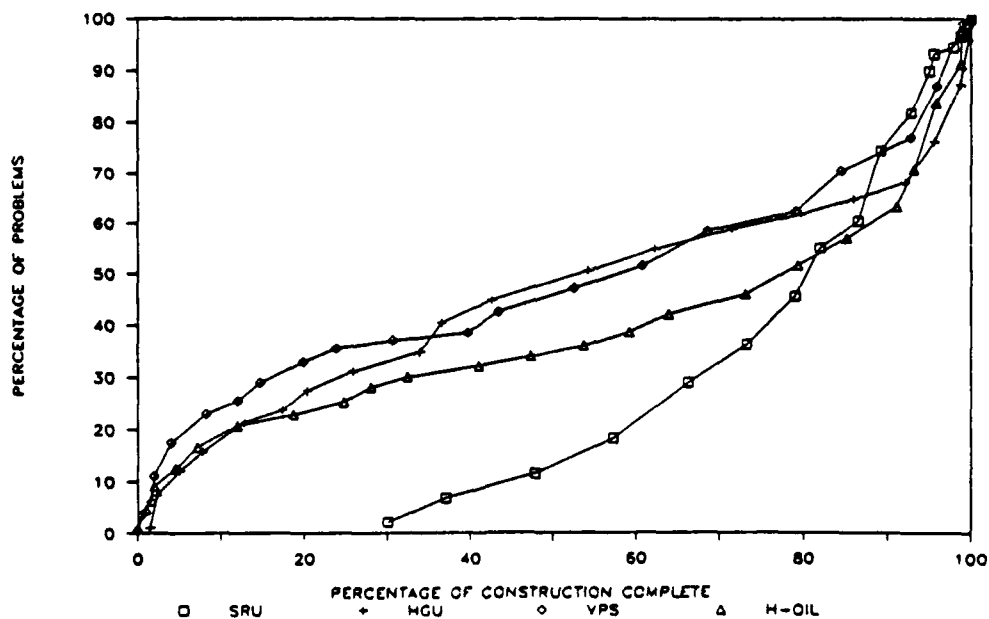


Figure 5.16b Design Contractor-Originated Problems--Percentage

5.5 Classification by Discipline

As covered in the section on design and construction sequences and the fast-tracking approach, certain tasks must be completed before others can start, while some activities are constructed before the design is completed. One way to check on the effect of this sequencing is to study the role the disciplines play in discovering problems. Therefore, this section is concerned with the problems as they were discovered by the disciplines. The questions to be evaluated are:

1. Which discipline discovered a problem?
2. At what point in the construction schedule did a certain discipline find a problem?

Table 5.5 presents a summary of the problems by discipline. This table shows that the percentages for each discipline are fairly close for all units except for some explainable differences.

The SRU has a low percentage for civil problems as compared to the other units. The biggest reason for this is that the procedure to write IOM's did not start until the unit was 30% complete and, as shown later in this section, most of the civil problems take place before this point in the construction process. The VPS had a higher number of civil

	NUMBER OF PROBLEMS					PERCENTAGE OF PROBLEMS				
	SRU	HGU	VPS	H-OIL	TOTAL	SRU	HGU	VPS	H-OIL	TOTAL
CIVIL	24	98	77	125	324	4.7	14.5	19.0	14.0	13.1
STRUCTURAL	30	32	16	39	117	5.9	4.7	4.0	4.4	4.7
BUILDING	1	8	0	2	11	0.2	1.2	0.0	0.2	0.4
EQUIPMENT	42	82	48	131	303	8.3	12.2	11.8	14.7	12.2
PIPING	132	151	75	253	611	26.0	22.4	18.5	28.3	24.6
ELECTRICAL	114	119	74	146	453	22.7	17.6	18.3	16.3	18.3
INSTRUMENTATION	157	177	110	189	633	31.0	26.2	27.2	21.2	25.5
PAINT/INSULATION	6	8	5	8	27	1.2	1.2	1.2	0.9	1.1
TOTAL	506	675	405	893	2479	100.0	100.0	100.0	100.0	100.0

Table 5.5--Problems Classified by Discipline

problems due to a decision by the construction contractor to use a ringer crane during equipment erection that was not originally planned and caused a change in the design and construction sequencing.

The disciplines of Paint/Insulation and Building did not have many problems on this project and will not be used in further analysis. It is believed that these two categories are fairly straight-forward and, in a cost-reimbursable contract, most problems can be solved in the field; therefore, correspondence back to the home office would be unnecessary.

Equipment problems are higher for the H-Oil than the other units. This is not surprising since the high-pressure, high-temperature vessels and supporting equipment represented the latest technology and was very complex. The SRU was designed from an existing unit and was expected to have fewer equipment problems.

Piping and Electrical disciplines represent the majority of work on an industrial project and are expected to have the most problems. Piping problems are high for the H-Oil due to the more stringent requirements dealing with pipes operating at high-

pressure and high-temperature.

The high percentage of problems associated with Instrumentation was a surprise, but not totally unexpected by the engineering staff. Throughout the project, the engineering staff felt that the Instrumentation group was not as proficient as the other groups, and this study confirmed their suspicion. Instrumentation represented approximately 13% of a unit's labor manhours; however, this discipline represents the area of the fastest changing technology as detectors and controls are now being installed to automate the monitoring of the process. Increased problems should not be unexpected.

Except for some variation, the percentage of problems for each discipline was fairly close which implies that estimates of the number of potential problems could be made from earlier constructed units. However, one of the weaknesses of this documentation is that the exact cause of a problem cannot always be found. Therefore, it must be cautioned in this section that the problem is not necessarily confined to the discipline that originated the memo because, while the memo designates who discovered the problem, it does not detail the exact cause. To discover the

cause, individual problems would have to be studied and, even then, only a guess could be made. For example, an interference problem between a pipe and a conduit run which is discovered by electricians does not tell us the exact problem. We do not know whether the interference problem was the result of improper design of piping, improper design of the conduit, or poor construction techniques in either piping or electrical. Still, the information that an interference problem exists is the first step in the gathering of information to correct the problem and avoid repetition in the future.

Figures 5.17 thru 5.22 graphically present the results over the construction phase of the project. The abscissa is labeled "Percentage of Construction Complete" and represents the actual construction progress for each unit. The ordinate shows, in Figure a, the cumulative number of problems identified by a particular discipline for each unit or, in Figure b the percentage of problems identified by a particular discipline for each unit. An extra curve is shown on the b graph which represents the typical progress for each discipline throughout the construction phase of the project. It can be observed in the b graph that

the problems for each unit approximates the same line or curve as the discipline's typical progress. This implies that the problems are not just confined to one stage of the project, such as the start for each discipline, but continue throughout the full cycle.

Figure 5.17 shows the Civil discipline. It can be readily observed that 80% of the problems were discovered by 30% construction complete for the three units where memos were available. The memo system started when the SRU was at the 30% point, so speculation is that the civil problems were not documented using this means of communication.

Structural (Fig. 5.18), Piping (Fig. 5.19), and Electrical (Fig. 5.20) disciplines have problems throughout the entire project and correlate well with their actual construction schedule. With these disciplines, it can be seen that the problems continued at a fairly constant level and did not dramatically increase as the intensity of the work effort increased in the middle portion of the construction schedule.

Instrumentation problems (Fig. 5.21) follow the progress schedule, but the schedule for this discipline does not get busy until 40% of the project is complete. 80% of the problems occurred over the last

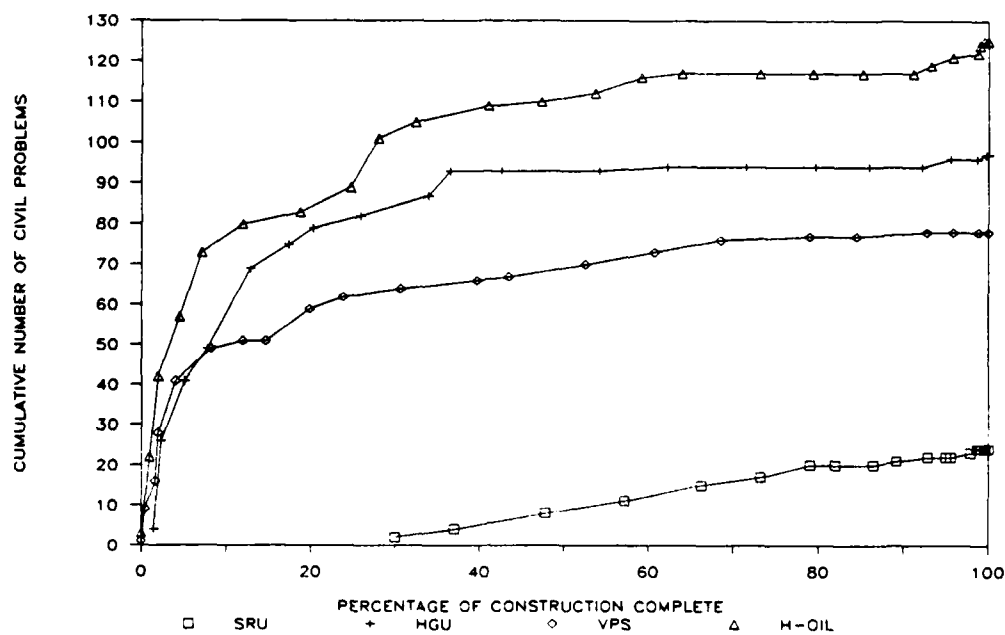


Figure 5.17a Civil Problems--Cumulative

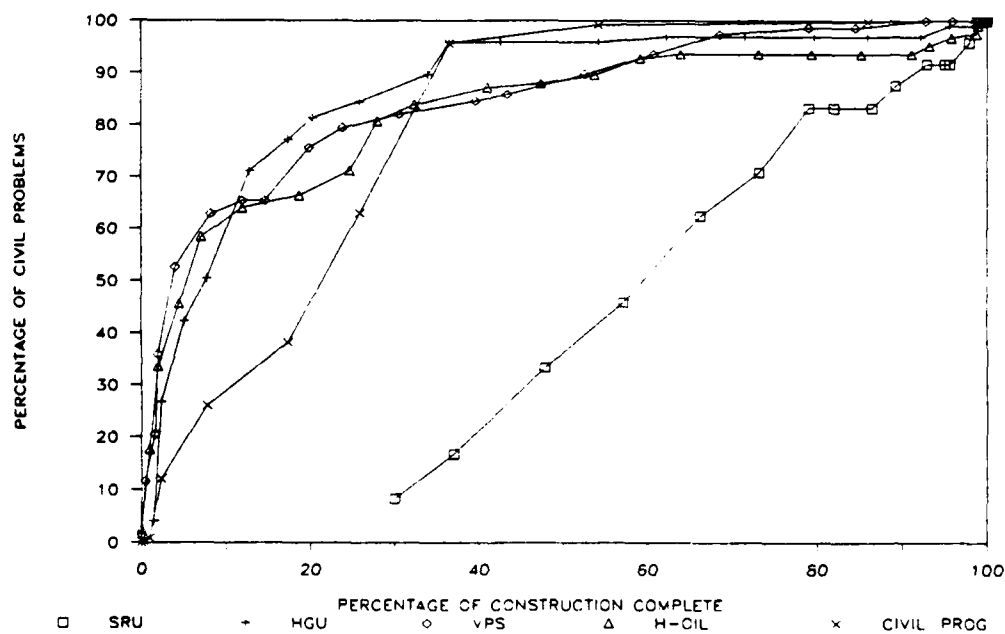


Figure 5.17b Civil Problems--Percentage

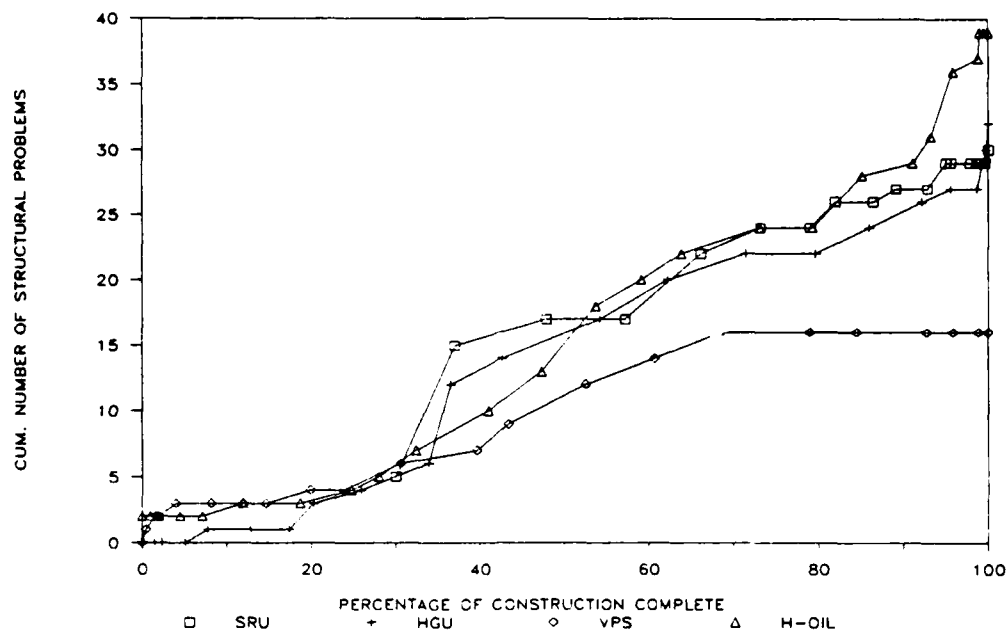


Figure 5.18a Structural Problems--Cumulative

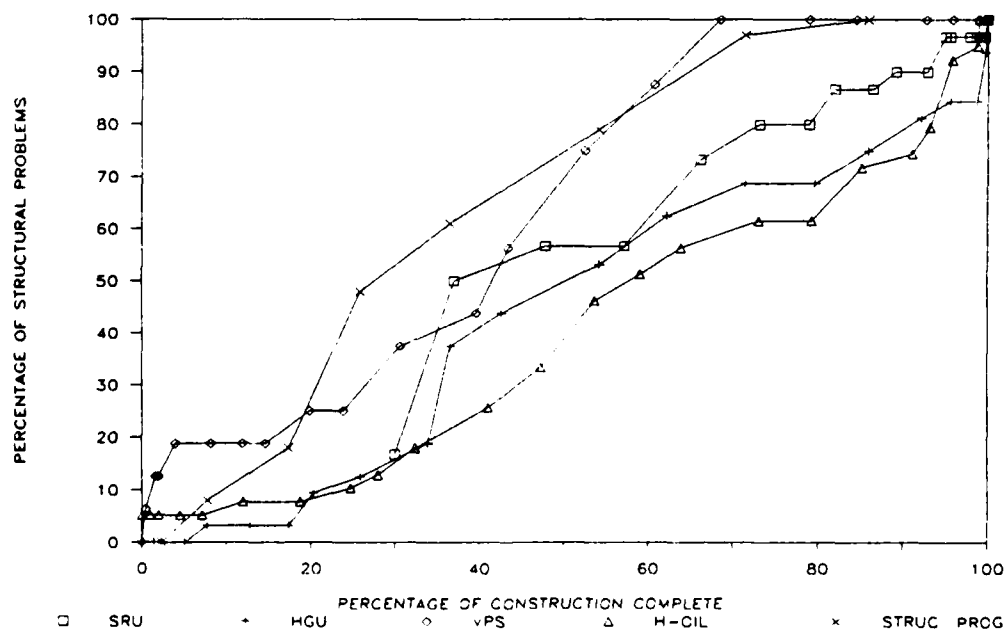


Figure 5.18b Structural Problems--Percentage

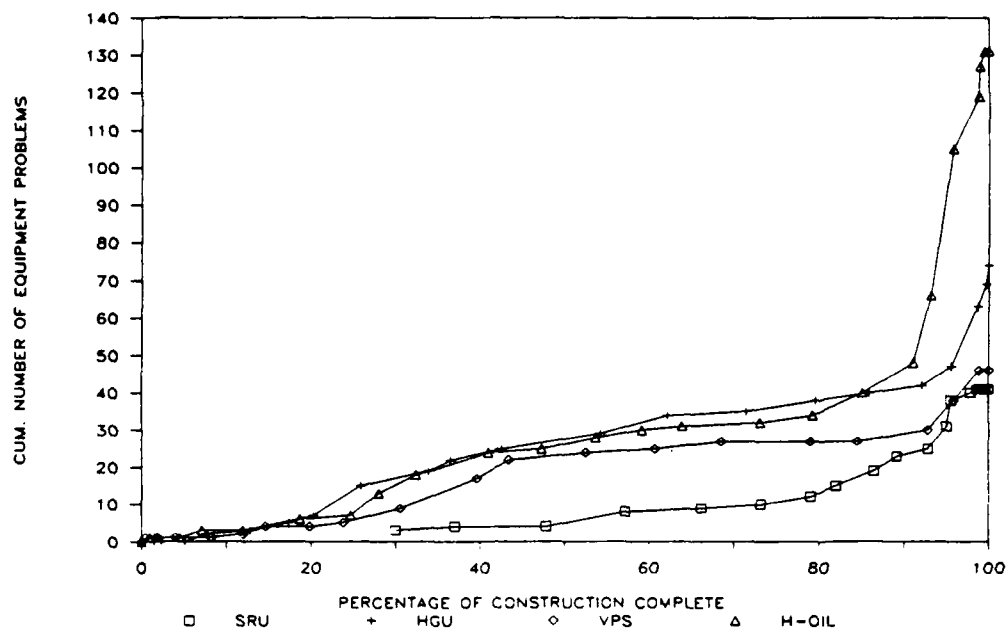


Figure 5.19a Equipment Problems--Cumulative

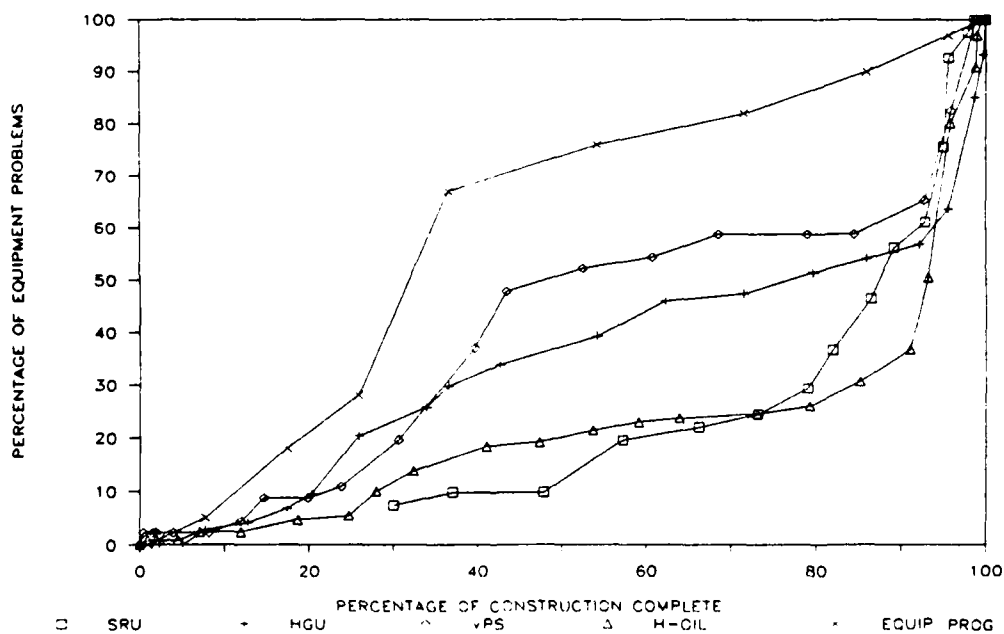


Figure 5.19b Equipment Problems--Percentage

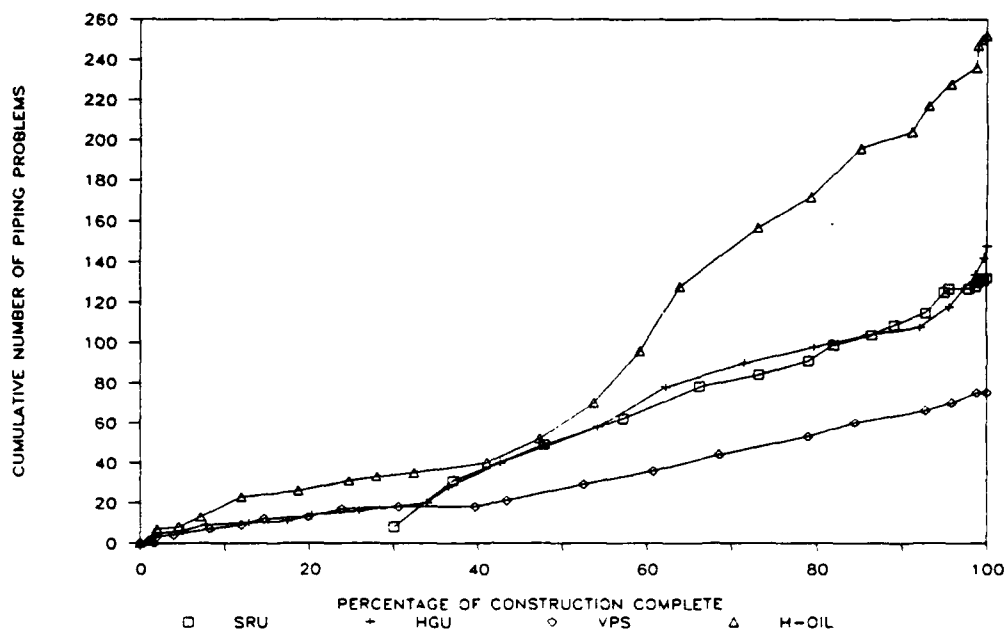


Figure 5.20a Piping Problems--Cumulative

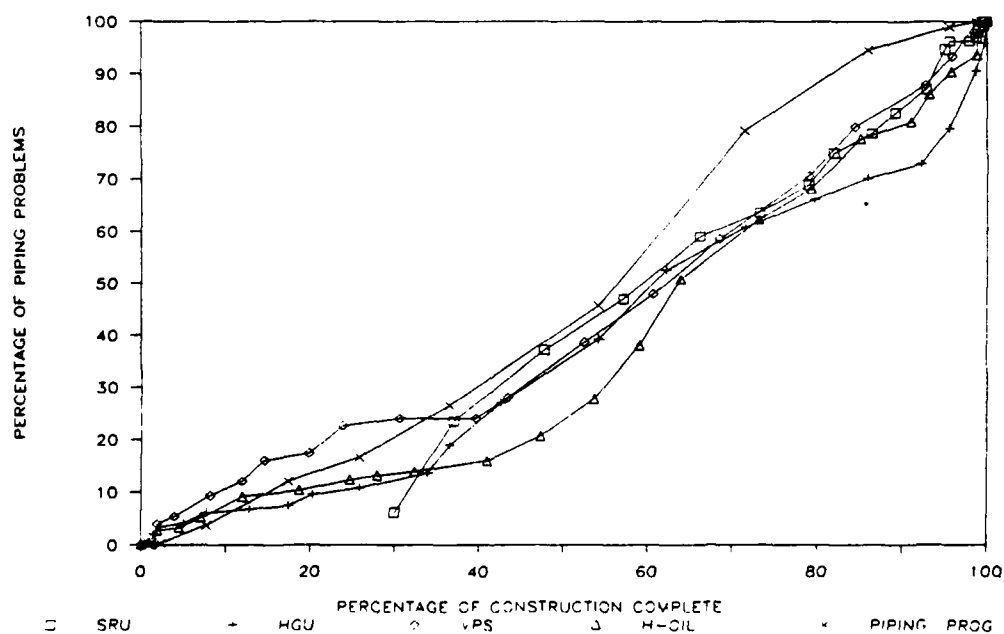


Figure 5.20b Piping Problems--Percentage

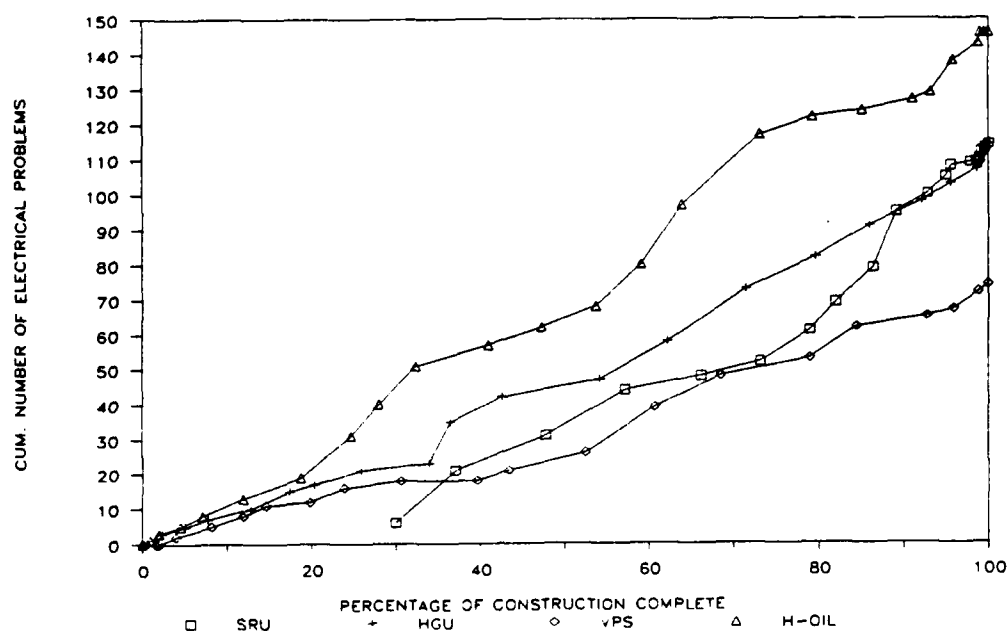


Figure 5.21a Electrical Problems--Cumulative

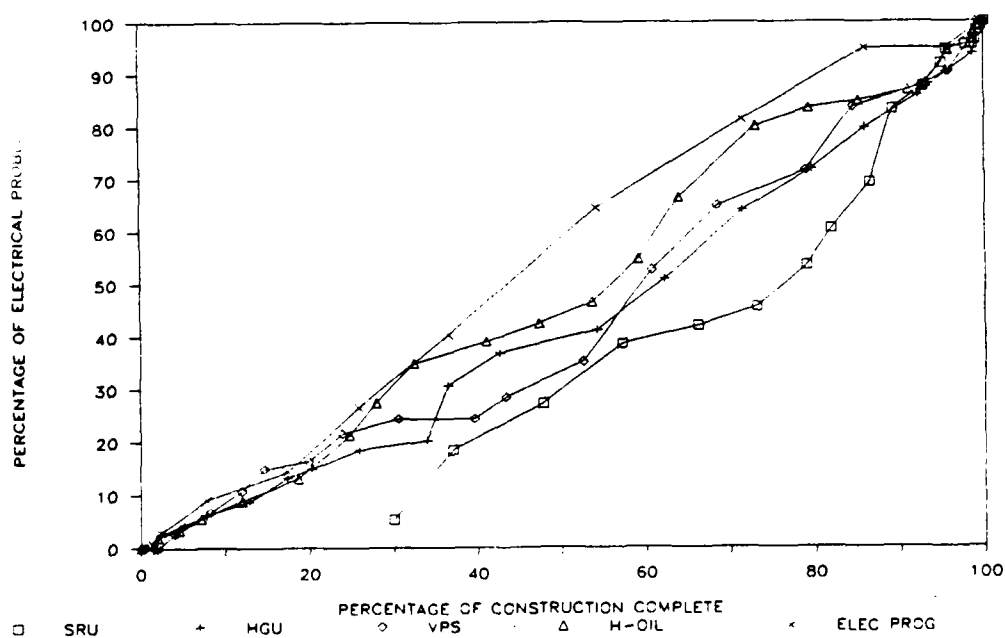


Figure 5.21b Electrical Problems--Percentage

40% of the project; therefore, any problems with this group can become critical as start-up approaches.

The Equipment discipline (Fig. 5.22) appears to be the one discipline that does not follow its actual progress. More problems are found in the late stages of construction--over 40% of the problems occur in the last 10% of the project. This means that the equipment is arriving on-site and installed without too many problems, but that problems are found during testing and start-up. Earlier testing may eliminate some of these problems.

5.6 Summary

This chapter contained preliminary data to determine if the design-related problems for each unit followed the same trends and had the same characteristics throughout the construction phase. Although there were many different factors that entered into the design process, observations based on both the tables and graphs confirmed this belief.

The largest categories of problems were Drawings, Schedule, and Design. Drawing problems were found throughout the project for all units. A large

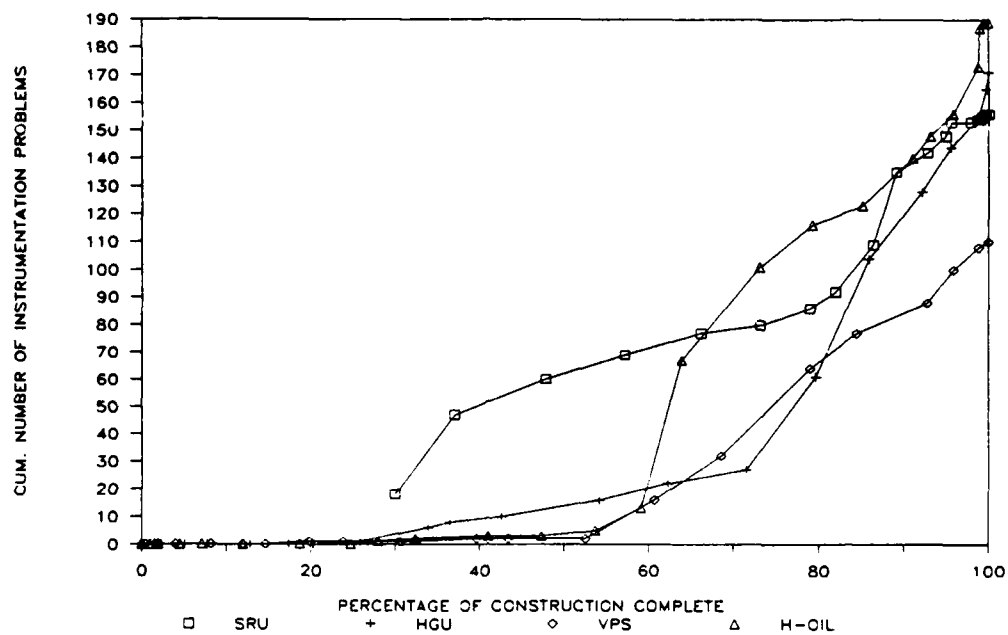


Figure 5.22a Instrumentation Problems--Cumulative

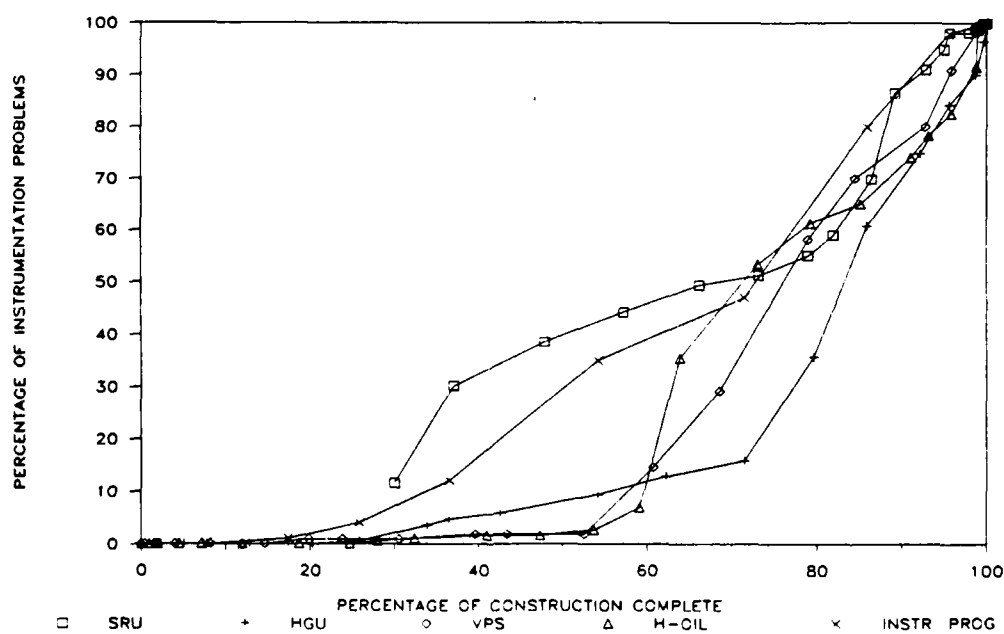


Figure 5.22b Instrumentation Problems--Percentage

number of Schedule problems occurred at the beginning of construction for each unit, while the largest percentage of Design problems occurred over the last 20% of the construction of each unit.

It was observed that the design contractor originated more IOM's as the technology became more complex. The owner originated memos mostly at the beginning of the project and during the start-up phase. The construction contractor originated most of its memos when the peak work force was on-site.

Instrumentation, Piping, and Electrical disciplines originated the largest percentage of memos. Piping and Electrical represent the largest amount of work so their appearance as leaders of problems is expected, but Instrumentation represented only 13% of the direct labor manhours. Instrumentation had problems due to its rapidly changing technology. Due to the increased emphasis on automated controls, managers should expect to see a high percentage of problems in this discipline in future projects until this technology matures.

The next chapter takes the analysis one step further. Statistical tests are utilized to determine if significant relationships between variables exist.

Finally, in order to find methods of predicting the occurrence of problems later in the project, various techniques are explored.

CHAPTER 6

ANALYSIS OF RESULTS

In Chapter 5, the timing of the discovery of problems was discussed. Early discovery should lead to different problems dominating different units throughout construction as management solves these problems. The figures in Chapter 5 indicate that similar problems were discovered for all units at approximately the same time. This leads to the conclusion that the problems were not totally a function of the sequence in which the units were constructed.

This led to an investigation into possible causes of problems. Possibilities included problems being a function of process complexity, percentage of the project complete, percentage of discipline progress complete, the design sequence, the construction sequence, the experience of the design team and the construction crews, or other factors not mentioned. There are numerous combinations that can be investigated, but certain parameters will account for most of the problems and explain the differences between units and disciplines. Therefore, this study

will attempt to examine some of these parameters--based on the available data.

The IOM's provided information concerning the timing of problems and who discovered the problems. Knowing the type and timing of certain problems does not directly lead to the answer of what caused these problems, but it lays the groundwork for further research to answer why a problem occurred and the possible elimination of that problem. Therefore, a preliminary hypothesis was developed to see if the number of problems were dependent upon process or technical complexity, design manhours or construction manhours. Problem dependencies, problem deviations and problem relationships were analyzed to test this general hypothesis.

Next, forecasting models are developed to predict the number of problems. Finally, a brief look at the potential economic implications completes the analysis.

6.1 Problem Dependencies

As stated earlier in this study, there were three important facts that could be obtained from the memos: problem category, organization, and discipline

of originator. Questions to be answered include:

1. Are these factors independent of each other?
2. Are certain problem categories dependent upon organization or discipline?

To answer these questions, contingency tables were used. Contingency tables are developed to test the independence of two variables and checked for significance using the chi-square distribution. Three contingency tables were set-up:

1. Problem category and discipline of originator
2. Problem category and organization of originator
3. Discipline of originator and organization of originator.

The null hypothesis was that the two factors are independent of each other. If the chi-square test showed that the calculated value was significant, then the two variables would be dependent. Informal observations of the results could indicate which relationships contributed to the specific finding.

(Note: For all tests, the expected frequency in each cell must be at least five to ensure that the sample size is large enough. If any cell did not have at least five, then a row or column must be combined to get a proper distribution.)

6.1.1 Discipline and Organization

Results of contingency tables for discipline and organization are shown in Table 6.1. For all four units, the following disciplines were combined to ensure proper cell distribution:

1. Civil and Structural
2. Building, Equipment, and Paint/Insulation.

Note: The VPS unit did not have any Building problems.

Table 6.1--Results of Contingency Table--Discipline and Organization

	χ^2	$\chi^2_{.05}$	D.F.
SRU	58	15.5	8
HGU	142	15.5	8
VPS	162	15.5	8
H-OIL	98	15.5	8

χ^2 Calculated value D.F. Degrees of Freedom

$\chi^2_{.05}$ Critical chi-square value

As seen in Table 6.1, all units show higher calculated chi-square values than expected; therefore, the null hypothesis can be rejected and the alternate

hypothesis that states the two variables are dependent is accepted. Observation of the results shows that Equipment and Instrumentation had the highest chi-square values.

The Equipment discipline had more problems originated by the owner than expected, and fewer than would be normally expected from a construction contractor. This is not surprising since the owner would be concerned with the actual equipment specified and would concentrate a large number of workhours in this area. Few memos should be originated in this discipline by the construction contractor since equipment installation should be fairly straightforward or is often subcontracted to the supplying vendor.

Instrumentation had more problems originated by the construction contractor than expected. This is disturbing to management since it implies that the instrument problems were not being caught in design, but reaching the field. Also, once a problem is discovered in the field, troubleshooting and rework to correct the problem become expensive in this discipline.

6.1.2 Problem Category and Organization

Results are shown in Table 6.2. Categories combined to complete analysis:

SRU	Design and Specifications Construction and QA/QC
VPS	Design and Specifications Construction, Procurement, and QA/QC
HGU	Construction and QA/QC
H-OIL	Design and Specifications Construction, Procurement, and QA/QC

Table 6.2--Results of Contingency Table--Problem Category and Organization

	χ^2	$\chi^2_{.05}$	D.F.
SRU	62	18.3	10
HGU	199	21.0	12
VPS	84	15.5	8
H-OIL	237	15.5	8

The null hypothesis can be rejected for all units, and the results show that certain problem categories were originated by specific organizations.

The two problem categories which had the highest contributions to the calculated chi-square were Scope and Drawings. Memos originated by the owner

concerning scope changes had very high observed frequencies, while the construction contractor had very low observed frequencies versus expected. The opposite happened in the second category. The construction contractor had more memos than was expected for Drawings, while the owner had fewer memos than expected.

The results for both categories are not unexpected. Scope changes should be started in the owner's organization and not the construction contractor's. Drawing problems are expected to be originated mostly by the construction contractor because if they were found in the review process, they would not become problems in the field.

The scope problems can be controlled by management so the rework caused by these problems is anticipated. Drawing problems are not necessarily controlled by management, but review procedures are; therefore, a certain amount of rework caused by these problems can be avoided. When reviewing the results of this study, management has to be concerned not necessarily with the fact that the contractor is originating those memos, but with the fact that such a large number of drawing problems were found.

6.1.3 Problem Category and Discipline

Results are shown in Table 6.3. Combined problem categories for each unit were:

SRU	Design and Specifications Construction and QA/QC
HGU	Construction and QA/QC
VPS	Construction and QA/QC
H-OIL	Design and Specifications Construction and QA/QC.

Combined disciplines for all units were:

1. Civil and Structural
2. Building, Equipment, and Paint/Insulation.

Table 6.3--Results of Contingency Table--Problem Category and Discipline

	χ^2	$\chi^2_{.05}$	D.F.
SRU	63	31.4	20
HGU	195	36.4	24
VPS	239	36.4	24
H-OIL	215	31.4	20

The null hypothesis can be rejected for all units. Significant observed differences for each unit are:

	<u>Problem Category</u>	<u>Discipline</u>
SRU	Drawings	Equipment *
	Design/Specifications	Instrumentation
HGU	Specifications	Instrumentation
	Scope	Equipment
	Drawings	Electrical
	Design	Piping
VPS	Specifications	Instrumentation
	Procurement	Equipment
	QA/QC	Equipment
H-OIL	Procurement	Equipment
	Construction	Civil
	Drawings	Equipment *
	Scope	Equipment

Note: All observed differences are where the observed frequency is more than the expected frequency except for those marked with an *, which means that the observed frequency is less than expected.

Results are fairly well distributed among the different disciplines and categories. However, problems in the Specifications category showed up in three of the units, and Equipment was the most influential discipline. The most revealing result is the Specifications category combined with the Instrumentation discipline. Management action could be taken to prevent specification problems, and different review procedures for future projects should be implemented.

The remaining statistically significant categories are probably not as much of a problem as the results show. Equipment problems are not independent of Procurement and Scope categories. Usually on an industrial project, substantial procurement problems can be expected and these are usually watched closely. Considering the amount of equipment ordered, these problems are not as significant as the results show. The Civil discipline had a high number of construction problems due to trouble with the pile driving operation. This is not unusual considering the southeast U.S. location.

The contingency tables for these tests did not provide as much helpful information as the other two categories.

6.1.4 Summary of Contingency Tables

Contingency tables test the independence of two variables. The following results were found:

1. In all cases, the null hypothesis was rejected and dependence shown.
2. Tests checking the discipline and the organization of the originator showed expected relationships between certain categories such as Equipment and Owner, and pointed out a trouble area in the Instrumentation discipline.

3. Testing Problem Category and Organization also showed dependence. Scope-Owner and Drawings-Construction Contractor were not unexpected; however, the goal should be to reduce the number of these problems.
4. The last set of tests, Problem Category and Discipline, once again pointed out problems in the Instrumentation discipline.

Overall, the contingency tables confirmed intuitive relationships and pinpointed trouble areas. Future projects can use this information to develop checks to find troublespots as well as review procedures where significant problems occurred.

6.2 Problem Deviations

The figures in Chapter 5 showed that problems for all units followed similar trends. Therefore, an investigation into when these problems occurred with respect to the discipline's progress could provide some of the answers as to why a particular problem occurs. The hypothesis to be tested is that the percentage of problems for each discipline varies proportionally to the discipline's progress.

To test this hypothesis, profile curves can be generated similar to those in Figure 6.1. Three types of curves explain the possible outcomes. Profile B (straight line) is the 45°-line which is the expected

outcome if the percentage of problems is proportional to the percentage of a discipline's progress. This means that problems occur throughout the time the discipline is active on the project and the problems increase at the same rate as the completed progress. Profile A (convex line) deviates from the curve by increasing quicker than the discipline's progress and then having fewer problems at the end of that discipline's activities. Profile C (concave line) also deviates from the 45°-line, but it drops below the baseline and then increases at the close of a discipline's activities.

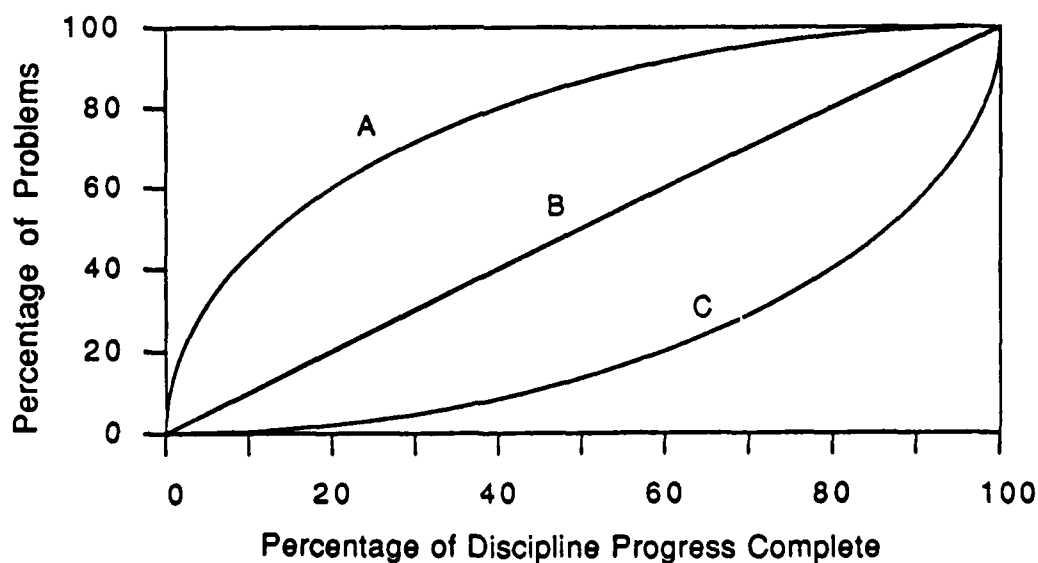


Figure 6.1 Example of Profile Curves

Of the three curves, Profile C is potentially the worst case since it shows that problems occur at the end of a discipline's activities. The closer to the end of the construction phase and the beginning of start-up a problem develops, the more expensive rework can become as more disciplines and systems are involved. Also, if management is unaware that a discipline is following the curve C pattern, there would be no indication that problems are going to occur until they are actually discovered.

Disciplines that follow curve A have a large number of problems develop quickly which should bring prompt managerial action. The increased attention will lessen their impact. Disciplines with problems that follow curve B follow the expected path and do not require the concentrated attention that the other two curves usually generate.

Figures 6.2 thru 6.7 show the curves for the major disciplines involved in this project. The curves show that Civil follows Profile A; Piping and Electrical follow Profile B; Structural and Equipment follow Profile C, while Instrumentation shows the most scatter--the SRU follows Profile A, the H-Oil and VPS are close to Profile B and the HGU follows Profile C.

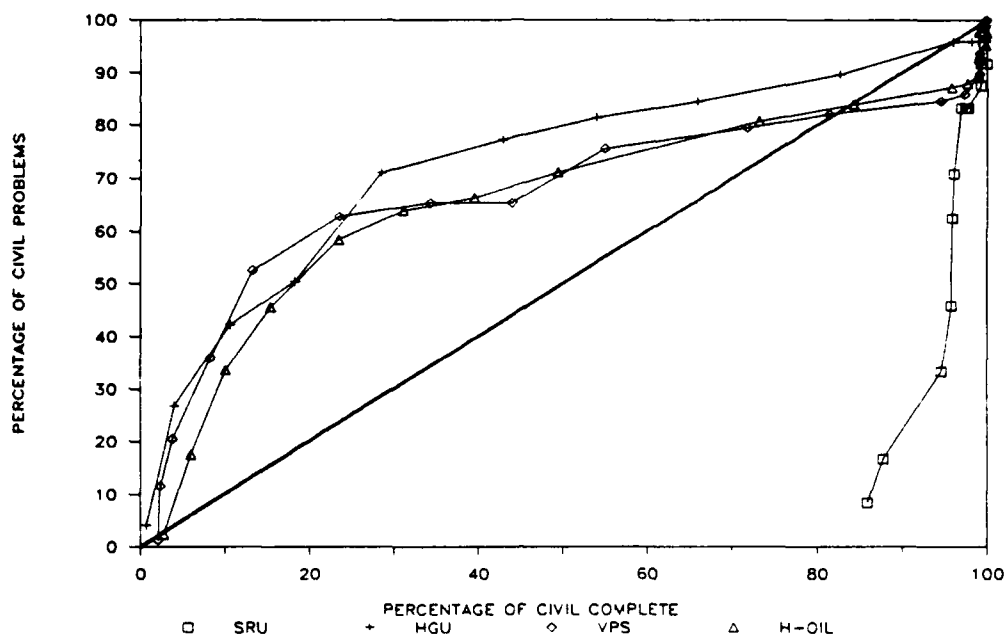


Figure 6.2 Profile Curve--Civil Discipline

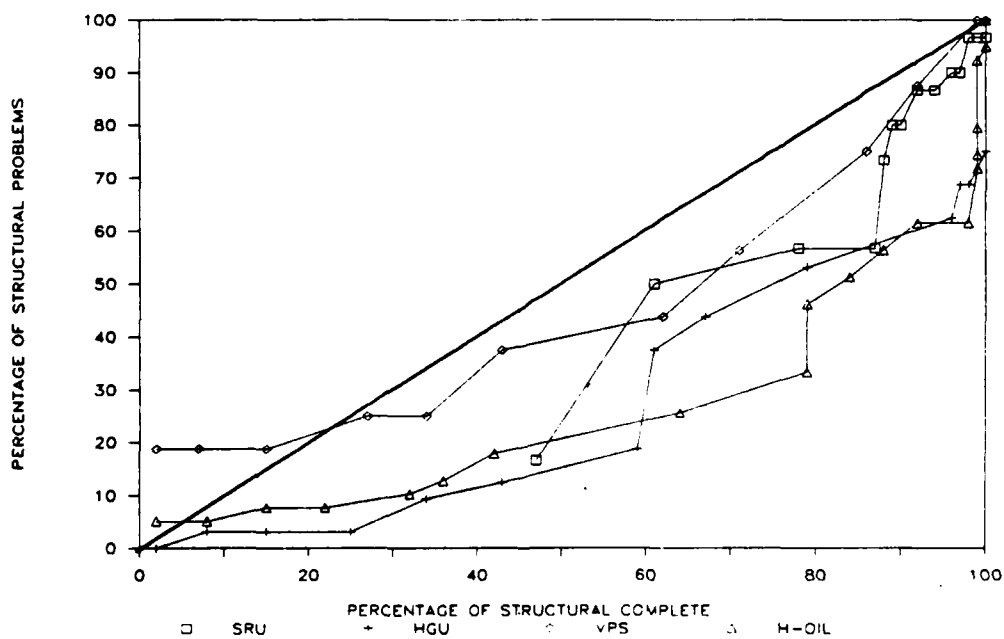


Figure 6.3 Profile Curve--Structural Discipline

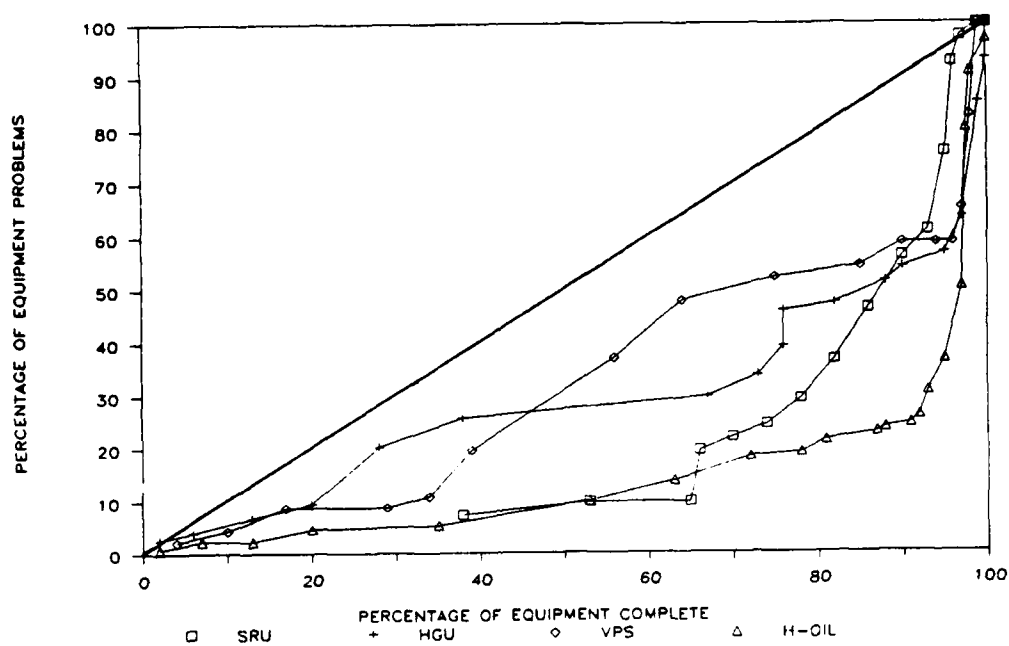


Figure 6.4 Profile Curve--Equipment Discipline

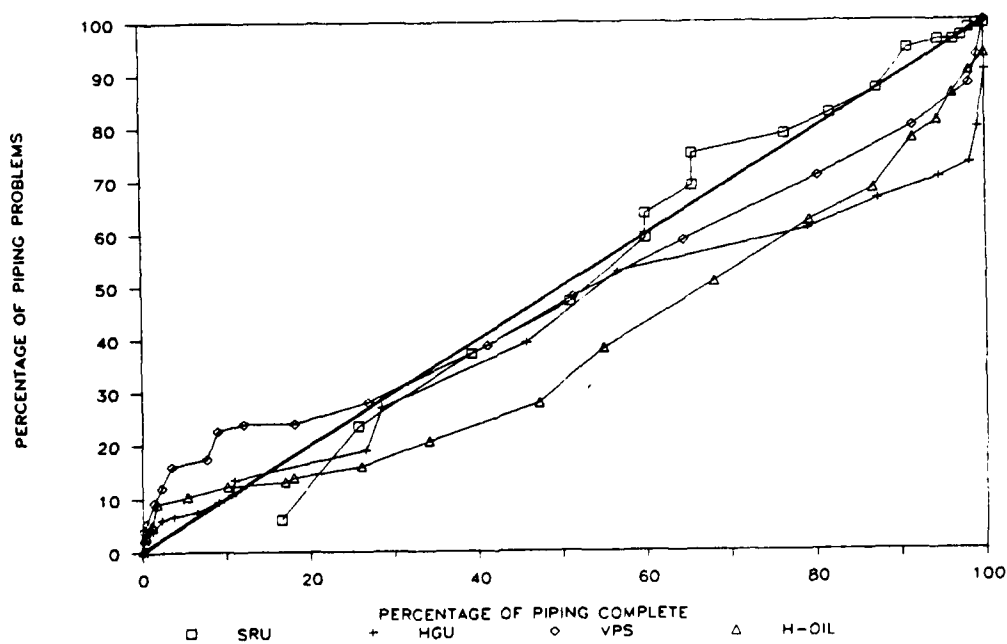


Figure 6.5 Profile Curve--Piping Discipline

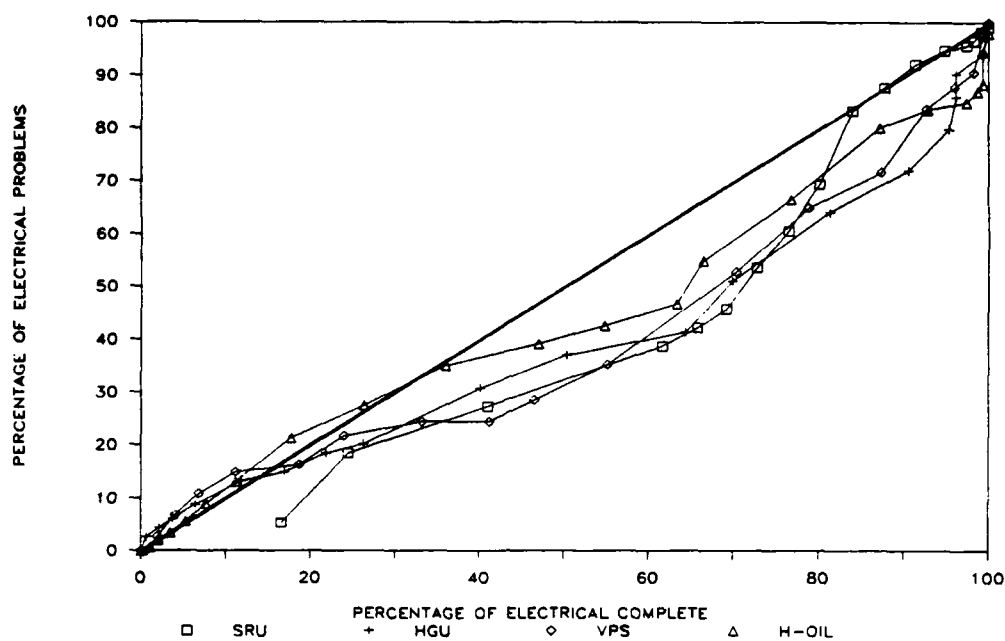


Figure 6.6 Profile Curve--Electrical Discipline

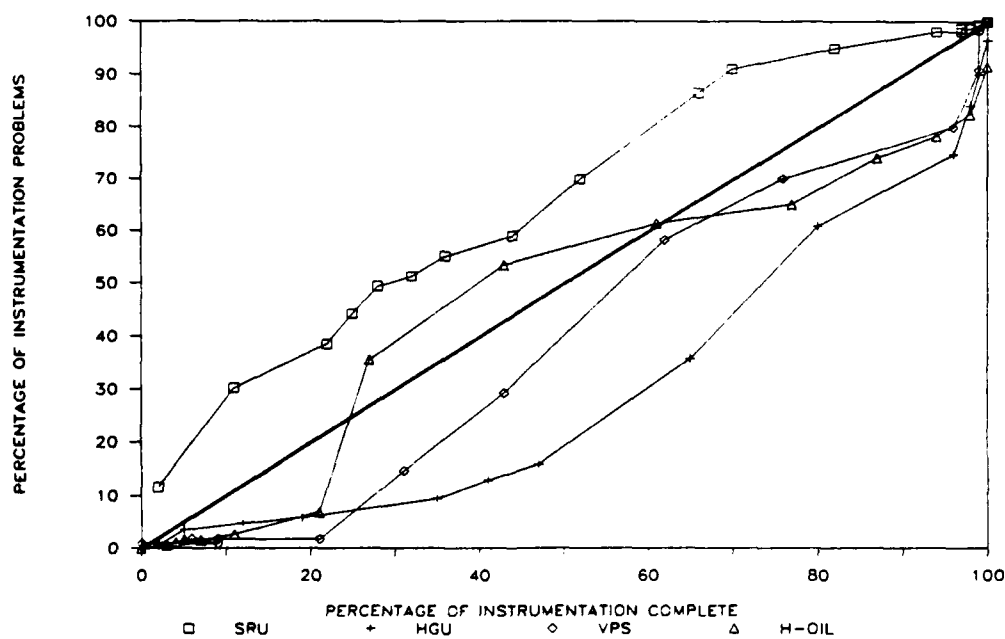


Figure 6.7 Profile Curve--Instrumentation Discipline

The first observation that can be noted from viewing these graphs is that the curves for each unit closely follow each other except in the case of Instrumentation. After viewing these curves and the previously presented information, it can be concluded that design-related problems do not vary during the construction phase of a project. The cause of the problem lies as expected in the design phase of the project. The different technologies and complexities of the units cause problems for the design team, but as stated earlier, the construction contractor used existing methods and technologies and did not actually cause many of the problems. If the construction technology or procedures would change, then more problems would originate from the construction phase. This is demonstrated by reviewing the Civil problems for the VPS. An unanticipated change to the planned method of erecting the vessels caused redesign problems and an abnormal portion of Civil problems in that unit.

Civil problems are a perfect example of a Profile A curve. (Note: The Civil discipline was approximately 80% complete on the Sulfur Block when the IOM's were started; therefore, the Civil problems are

not accurately documented for this study.) This means that the majority of Civil problems are discovered early and very few problems occur near the end. This seems reasonable since most of Civil problems should be discovered at the onset of the activity--excavation depths, location of foundations, erection of forms, etc. are all operations that need accurate information early and then the activity should proceed with little guidance. An example is the foundation. Accurate information on the location and size must be provided early. Once formed, concrete can be poured and finished to specifications without further design guidance.

Piping and Electrical disciplines follow Profile B with only slight deviations. Early deviations above the line are the result of underground activities that follow the same logic and explanations as the Civil discipline--problems arise at the beginning of the activity, but once solved, proceed smoothly. Later deviations drop below the baseline which indicates more problems than expected at the end of the activity. These problems occur during the testing phase of the activity which is near the end of construction. Implications of this finding will be

discussed later in conjunction with the Equipment discipline.

Structural problems show some scatter and follow Profile C. The cause of the scatter is the low number of structural problems in this project (see Table 5.5). The Structural discipline and the number of problems discovered represent approximately 5% of the total and probably do not have a major impact on the project. The Profile C curve results from design changes or redesign due to interferences or clearance problems, mostly with piping, that are not found until the piping is actually installed. Therefore, this profile will probably not change; however, new design technologies such as computer-aided design (CAD or CADD) should eliminate the majority of these problems.

The Equipment discipline followed a Profile C curve. This is the worst case for management since problems would not be found until the end of the activity. These problems are occurring during the testing period for the equipment. Major testing is usually done on a system basis with all equipment, piping, electrical and instrumentation completed instead of testing the equipment on an individual basis. Therefore, when problems occur, extensive

rework is often needed. Research is needed in this area--the goal should be to find methods to change the equipment curve from a Profile C curve to Profile B or A. This may entail improving the quality control system or completely rethinking the method of installing and testing equipment.

The last discipline to be examined is Instrumentation. The expected curve would follow Profile C--more problems would be expected to occur during the testing of the equipment when the instrument's actual performance is being monitored. Due to the scatter involved, a detailed look at the type of problems that occurred and when they occurred was conducted.

6.2.1 Instrumentation Problems

Instrumentation had the largest number of total problems and the largest scatter of curves. To explain this, it must be remembered that Instrumentation represented the discipline that had a changing technology. Automatic controls and detection instruments were being utilized in lieu of operators and semi-automatic or manual instruments. Figures 6.8 thru 6.11 show the number of instrumentation problems in relation to the percentage of instrumentation work

completed. Results show various profiles and problem types for each unit.

Reasons for the different profiles can be explained by the sequence of construction, the complexity of design and the type of problems. The SRU was the first unit designed and constructed. Therefore, the first major peak was the result of (1) it being the first unit and all parties becoming familiar with procedures and working with each other and (2) a large number of drawing problems. The second peak occurs near the end of construction (testing) and this peak is expected.

The VPS did not have very many problems except for specifications. The technology for this unit was the best known, so the probable cause of these problems was the tendency to use previous specifications without carefully updating them to match the changes in instrumentation.

The HGU followed the expected pattern (although the VPS unit curve would be more desirable) where most problems occurred in the final half of the schedule. Specifications and Drawings were the two biggest problem categories. Specifications must be accurately detailed to vendors and the construction

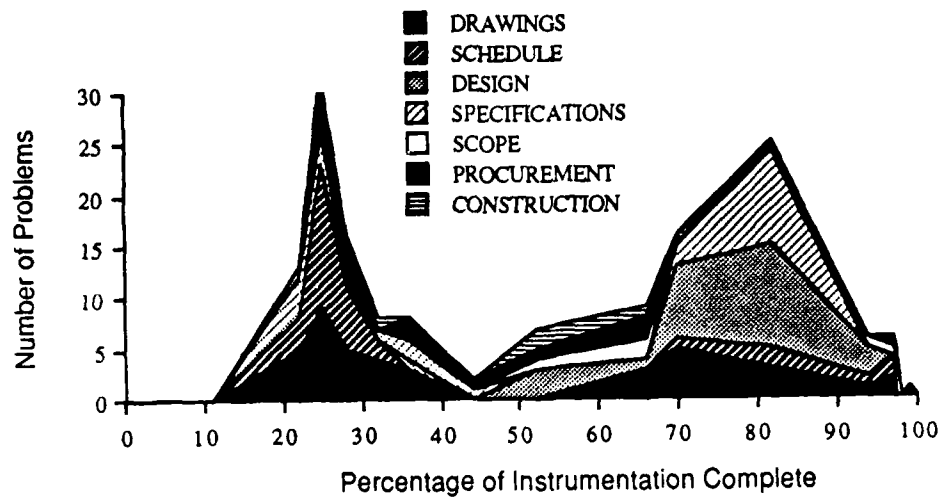


Figure 6.8 SRU Instrumentation Problems

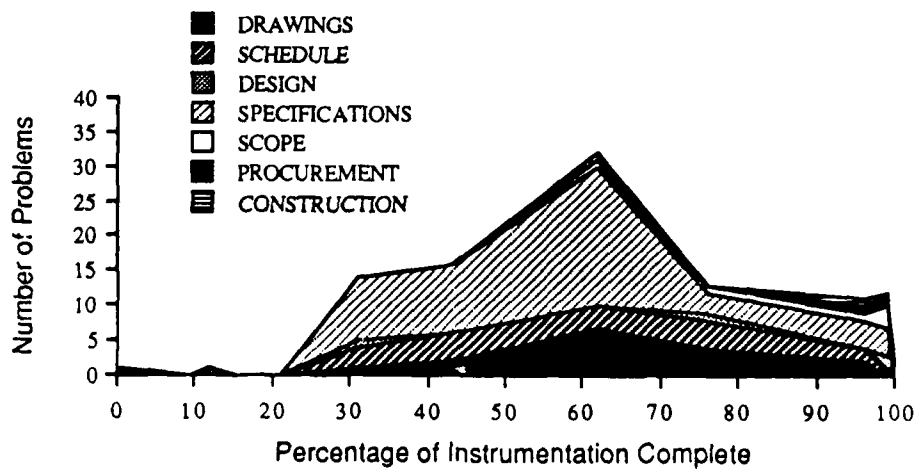


Figure 6.9 VPS Instrumentation Problems

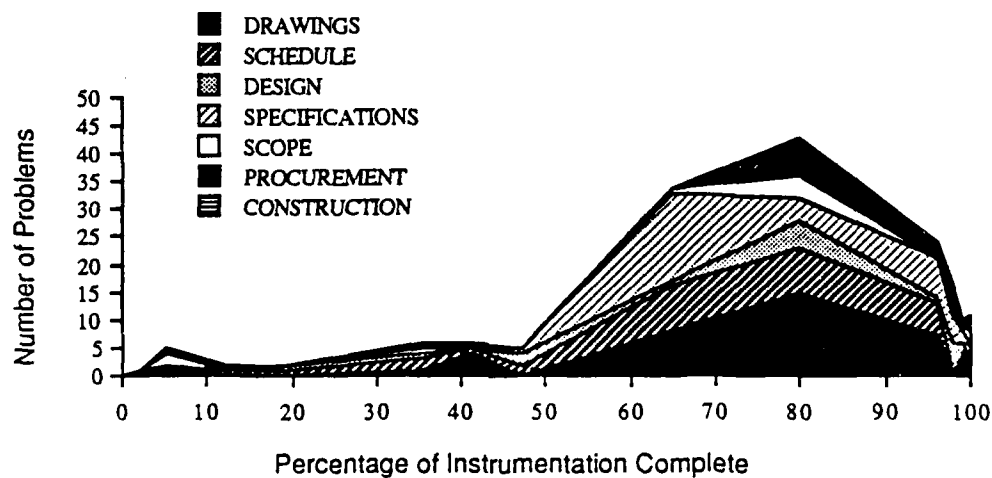


Figure 6.10 HGU Instrumentation Problems

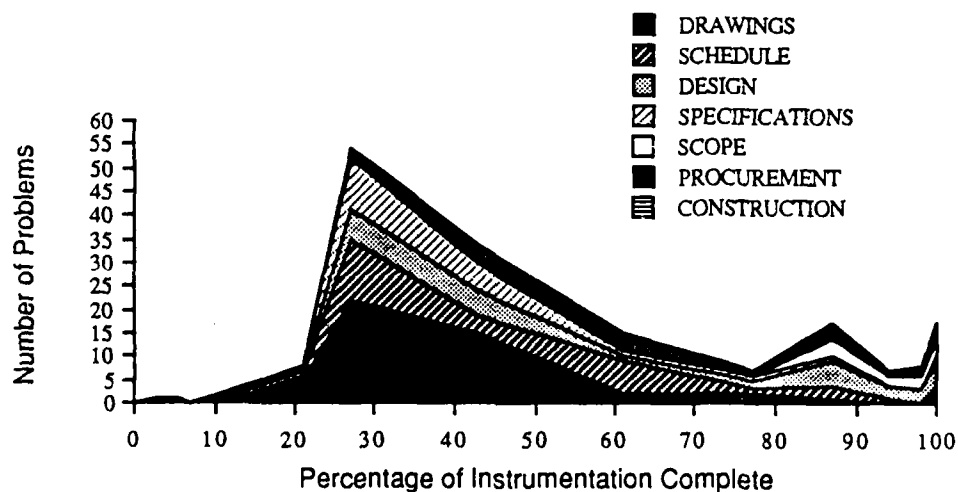


Figure 6.11 H-Oil Instrumentation Problems

crews. Drawing problems during this phase of construction are usually caused by incorrect design or field changes made to the drawings that did not show up until the check-out period.

The H-Oil had a larger than expected number of problems around the 30% instrumentation complete and then a slight increase in the number of problems at the end. The early problems included drawing, schedule and specification problems. It is believed that the same problems existed here as in the other units, but they were discovered earlier for this unit. Reasons for early discovery include the fact that this was the last unit constructed and that this was considered the most technologically complex process unit and had more management attention in the beginning of construction.

Although each profile differed, a pattern can be seen by studying the various Instrumentation profiles. Indications are that the timing of the problems can be changed and the possible effects minimized. The H-Oil problems were discovered earlier as a result of recognizing the problems that occurred on the other units and increased management attention during the earlier phases of construction.

6.2.2 Summary of Problem Deviations

The IOM's provide a link for design-related problems from the construction phase to the design phase. Unfortunately, the IOM's do not show the actual cause of the problem and there is presently no documentation that exists to trace the actual cause of a problem. However, the strength of the IOM's is that they provide identification of the problem, the discipline of the originator and the timing of the problem. Modification to include estimated or actual rework hours to solve the problem would help identify the impact of these problems.

After reviewing the results in Chapter 5 where all units exhibited similar characteristics for each discipline, it was decided that a more detailed investigation was warranted. A method to study problem deviations was developed by testing the hypothesis that the percentage of problems for each discipline was linearly proportional to the percentage of a discipline's completed progress.

The results of this analysis showed that Piping and Electrical were linearly proportional to the completed progress, Civil problems were discovered at the beginning of that discipline's activities,

while Structural, Equipment and Instrumentation problems occurred towards the end of the discipline's activities.

The late-occurring problems represent the area of most concern for management since there is no indication that problems exist until they actually occur. Equipment and Instrumentation disciplines accounted for approximately 35% of the problems and further study into the method of testing and the quality control system should be completed.

Finally, Instrumentation problems were analyzed for each unit. The results showed that the first unit completed, the SRU, had an early peak of drawing and scheduling problems followed by a second peak at the end of the project. Specification and drawing problems dominated the VPS and HGU (the second and third units constructed) with the majority of problems occurring in the last 50% of instrumentation complete. It was on the fourth unit constructed, the H-Oil, that the problem occurrence was shifted to the first half of the progress curve where the impact could be lessened.

6.3 Problem Forecasting

As stated in the introduction, one of the reasons for doing historical research is to predict future trends. The IOM's provide an excellent record of the time a problem was discovered and who discovered the problem. The results were consistent for all four units of this project; therefore, further studies were made to determine if any models could be developed to predict the number of problems and when they would occur. The models involve time series analysis and regression analysis.

6.3.1 Forecasting Using Time Series Models

Accurate forecasting of future problems and investigating if one series could predict another time series through the use of a transfer function were the reasons for doing a time series analysis using the ARIMA model. It was decided to test scope and drawing problems for all four units to see if the time series might be a useful technique for analyzing design-related problems. Figures 6.12 thru 6.15 show scope and drawing problems for the four units. It was hoped that ARIMA models could be developed for each series and that there would be a cross-correlation which

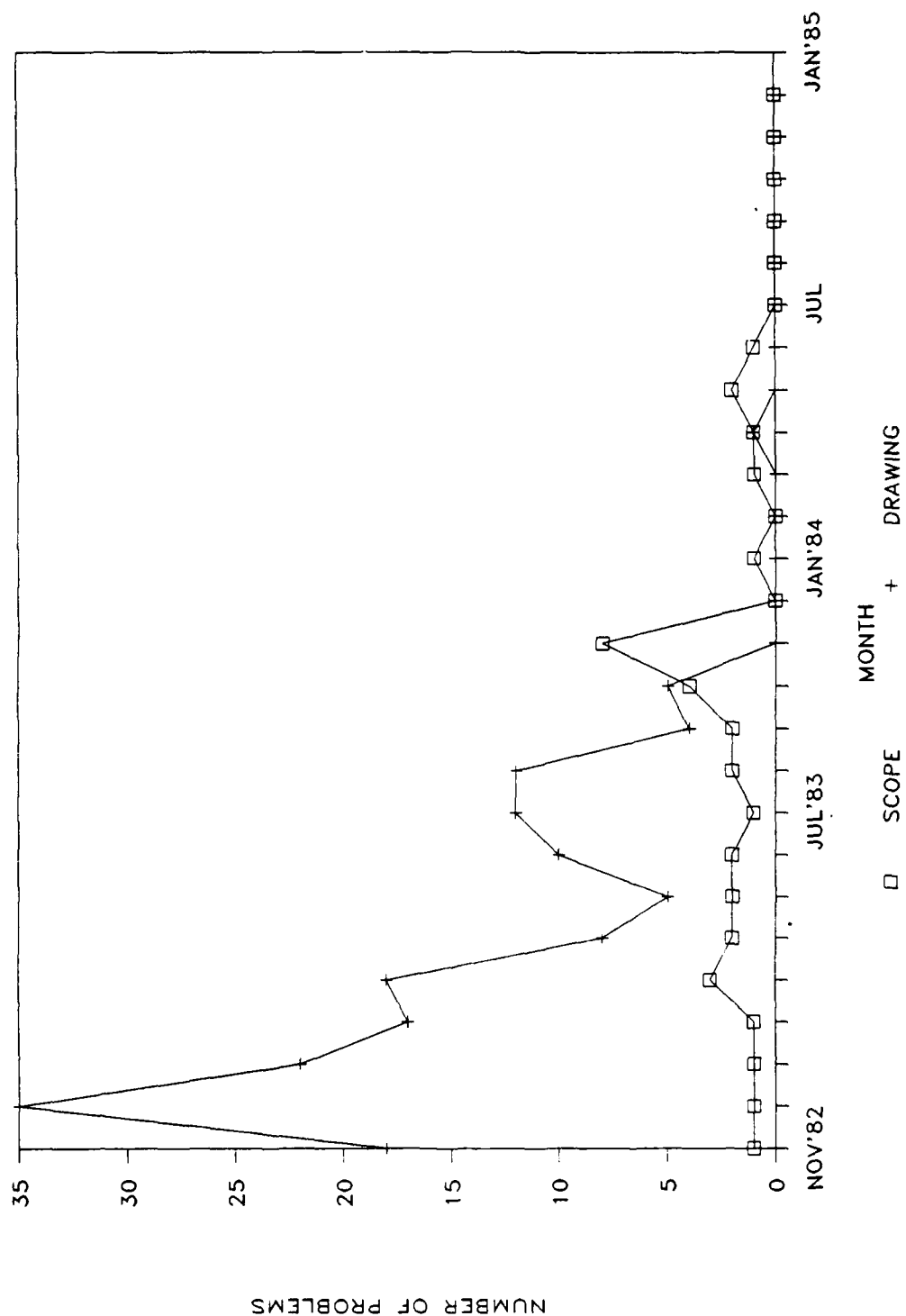


Figure 6.12 SRU--Scope and Drawing Problems

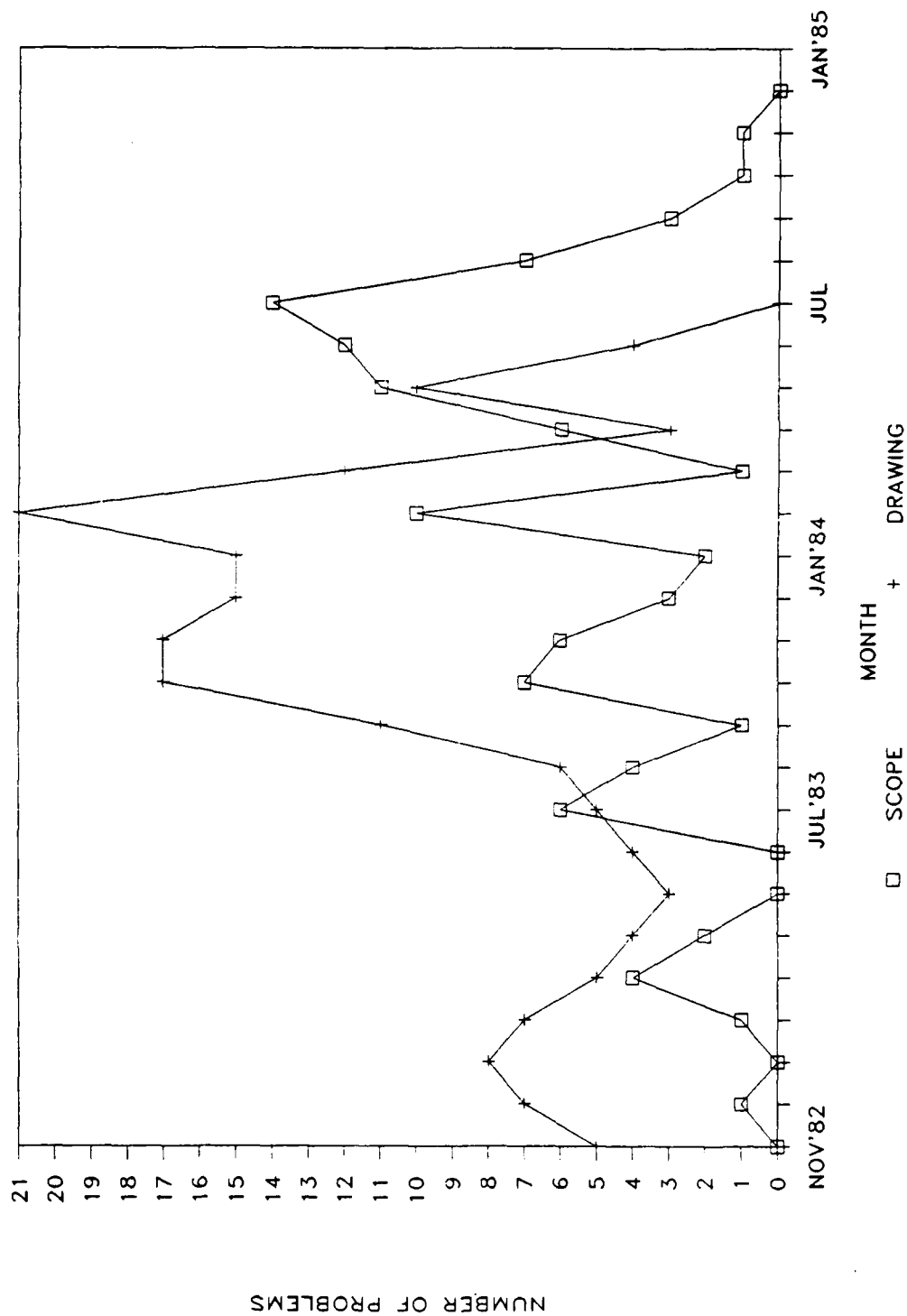


Figure 6.13 HGU--Scope and Drawing Problems

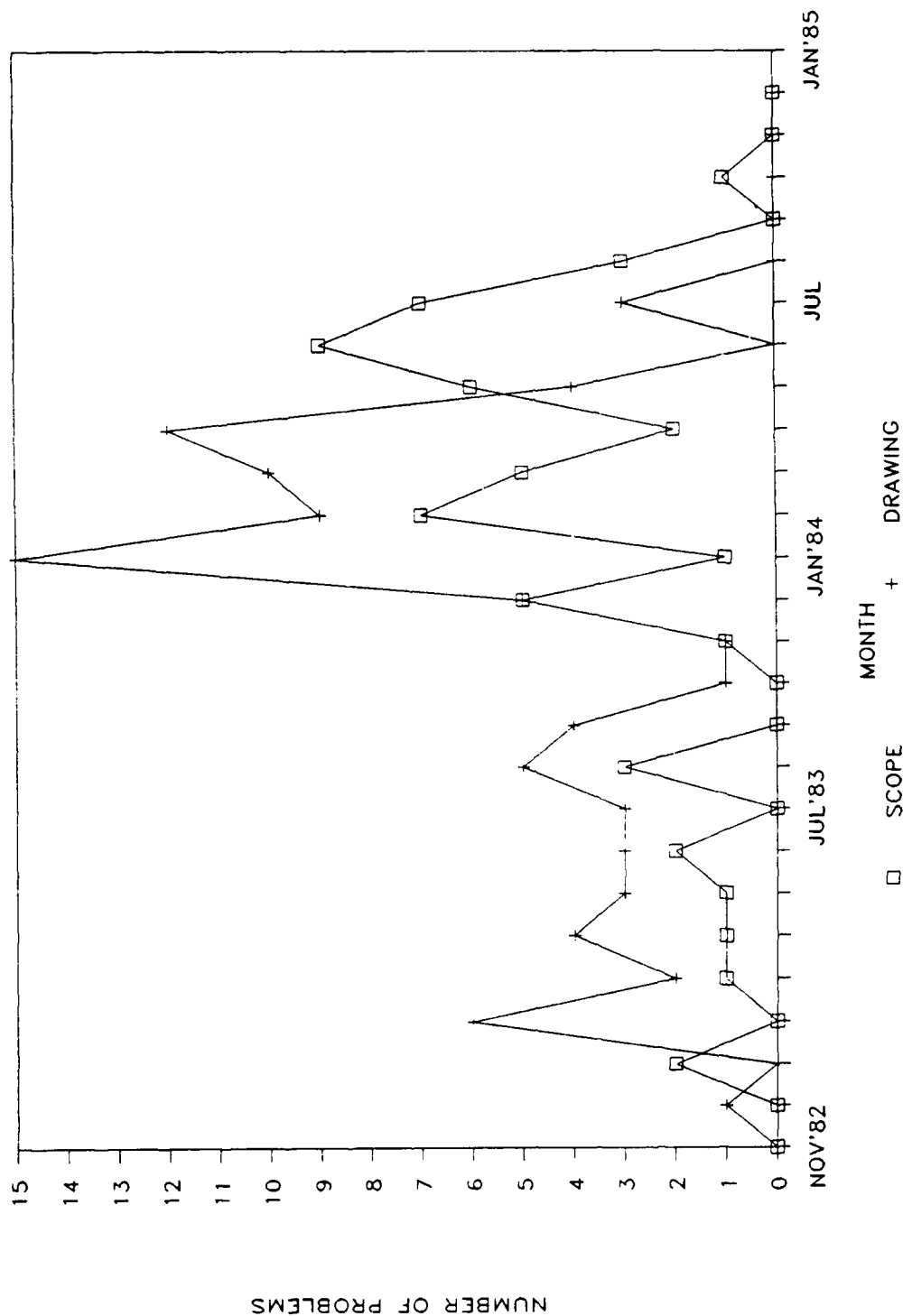


Figure 6.14 VPS--Scope and Drawing Problems

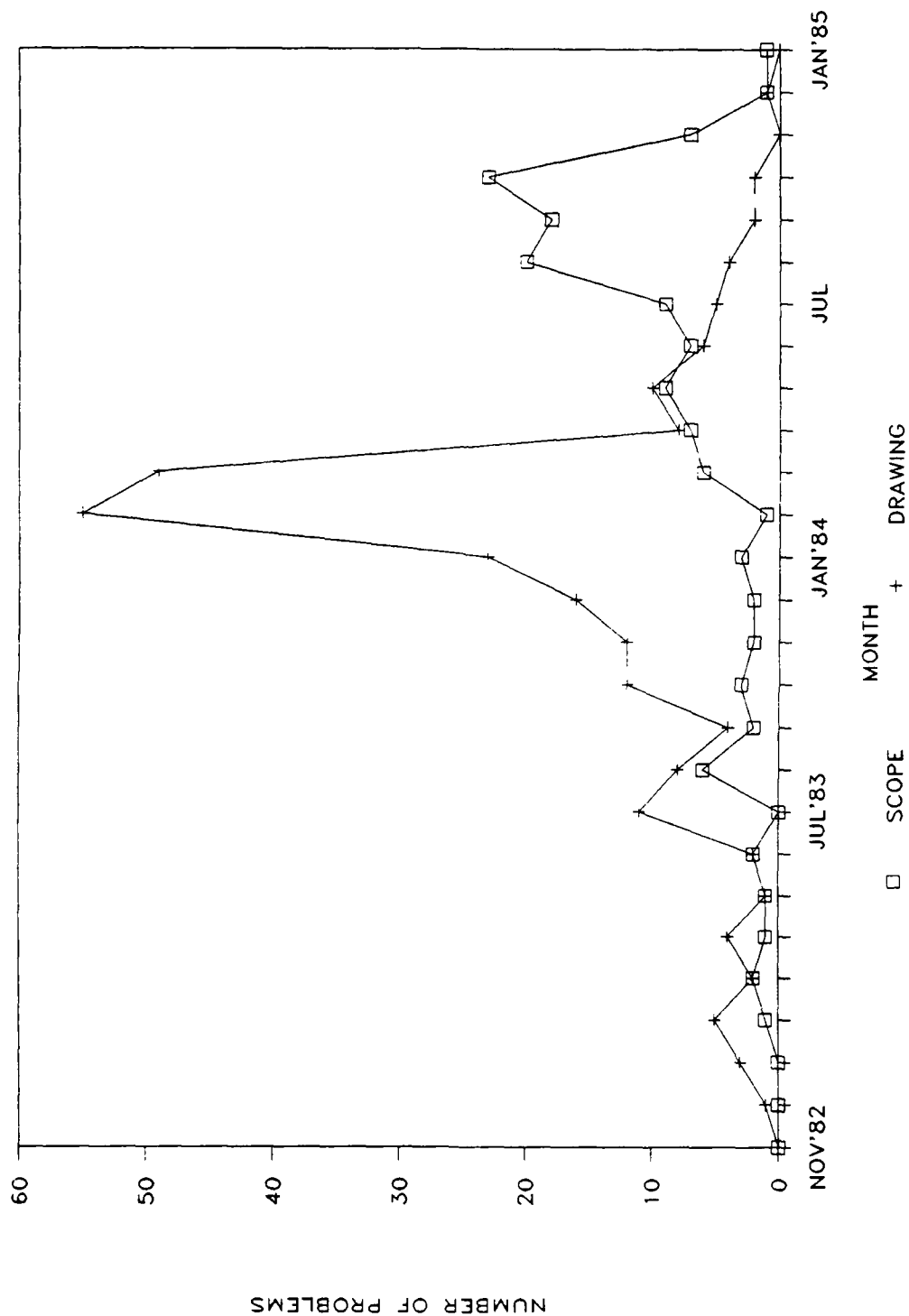


Figure 6.15 H-Oil--Scope and Drawing Problems

would show a relationship between scope and drawing problems.

The reason for choosing scope and drawing problems includes the fact that scope problems have been identified by the Business Round Table (1982, 16) as one of the leading factors of cost overruns in construction, and drawing problems had the largest percentage of design-related problems in this study. If there was a correlation between scope and drawing problems, then changes in scope would partially explain the reason for some drawing problems. This would be significant because these problems would not exist without the scope changes. This would demonstrate the cascading effect that certain types of problems have on a project. Elimination of some problems could then eliminate others without further management action.

Preliminary analysis showed that each time series exhibits characteristics of a "random walk", which means that the shocks to the system were not dependent upon the previous data. Each series was transformed using a square-root function and differenced once to get a stationary series. Autocorrelations and partial autocorrelations were calculated to

try and identify an appropriate model. There were no significant correlations, implying a random walk series. Cross-correlations were then plotted to see if there was a relationship between drawing problems and scope problems. There were no significant relationships found between these two variables.

Preliminary observation of the remaining data showed similar results. Therefore, further analysis of different variables was not undertaken.

6.3.1.1 Critique of Time Series Analysis

Time series models have been useful models for predicting future values for data that varies with time. However, the time series model did not work very well for this project. Three reasons that the model did not work well were (1) the problems, (2) the time interval, and (3) the length of the project.

The design-related problems were not part of a dependent time series. The problems were not dependent upon past information to predict its classification or when it would occur. The problems formed a random walk. (It should be noted that some random walk series can be successfully modelled after differencing, but this did not happen in this case.)

For a time series, observations must be made

over equal time intervals. The problems were classified monthly, but the problems more closely followed the construction progress made on the project. Since each project has different activities of different durations, the actual progress for each unit was not completed at the same monthly intervals.

Finally, a time series usually needs a fairly long period of time to establish a pattern. Most references suggest a minimum of forty to fifty observations with a preferred number of 100. In construction, the time interval is relatively short. The construction phase of a project is usually less than three years. It is felt that a monthly interval would be necessary to provide the most accurate data; therefore, there would usually be less than thirty-six observations. In this project, there were approximately twenty-five observations per unit.

Because of the above reasons, time series analysis did not provide a good model to forecast future problems.

6.3.2 Forecasting Using Design Manhours

Throughout this study, evidence has pointed to the fact that design-related problems are a function of process complexity and design complexity rather than construction complexity. Therefore, a method of relating process and design complexity to problems was needed. A rough measure of process and design complexity is the design manhours used by each discipline. The assumption made was that the more manhours needed, the more complex the design process. It is realized that the process complexity and the actual detailed design complexity are separate issues, but the small sample size available on this project and the limitations of the documentation suggest that the treatment of complexity can be handled with one variable. Therefore, the variables used in this regression analysis were:

Independent variable: design manhours
Dependent variable: number of problems

Table 6.4 shows the design manhours for each discipline and Figures 6.16 and 6.17 show the plot of the number of problems versus design manhours.

(Note: Due to the breakdown of design, Civil and

Structural design manhours and their corresponding problems are combined into the Civil discipline.)

Table 6.4--Design Manhours for Each Discipline
(x 1000)

Discipline	H-Oil	HGU	VPS	SRU
Civil	93.1	43.6	48.8	34.7
Equipment	106.6	79.0	71.2	46.3
Piping	357.5	218.1	190.7	144.8
Electrical	95.1	62.1	54.3	23.2
Instrumentation	60.4	40.0	31.2	40.5

Figure 6.16 shows the number of problems versus design manhours with a look at the complexity of the units. It appears that as the technology of a unit moves from a mature technology (VPS and SRU) to the newest technology (H-Oil) that the number of problems and the design manhours for each discipline increases. This holds true even for Piping although the Piping design manhours are so much greater than the other disciplines. Lines are drawn to show this trend since it is hard to visualize at the scale used. This graph shows a trend that must be carefully

examined. The negative slope of these lines indicates that an increase in design manhours for a given technology should decrease the number of problems and could, theoretically, reach zero with a specific number of design manhours. Realistically, it is known that zero problems could not be reached and that there is a practical lower limit; therefore, the lines are shown tailing off to the right.

The important information to take from this figure is the trend that shows (1) as complexity increases, so does the design effort and potentially the number of problems and (2) at a certain level of technology, an increase in design manhours should reduce the number of design-related problems. A study of more projects as well as an attempt to isolate variables that would affect the results such as designer's experience, workload, design schedule, etc. would have to be undertaken before definite conclusions could be drawn concerning the benefit of increasing design manhours to reduce design-related problems.

The second design area to be investigated is the influence of different design groups on the number of design-related problems. Figure 6.17 presents the data as investigated. It appears that there could be

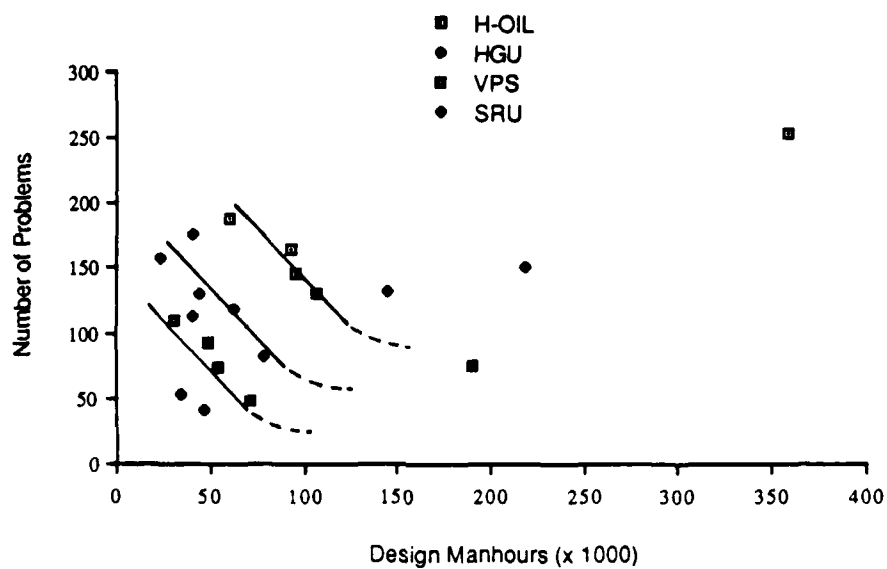


Figure 6.16 Plot of Problems versus Design Manhours (Categorized by Unit)

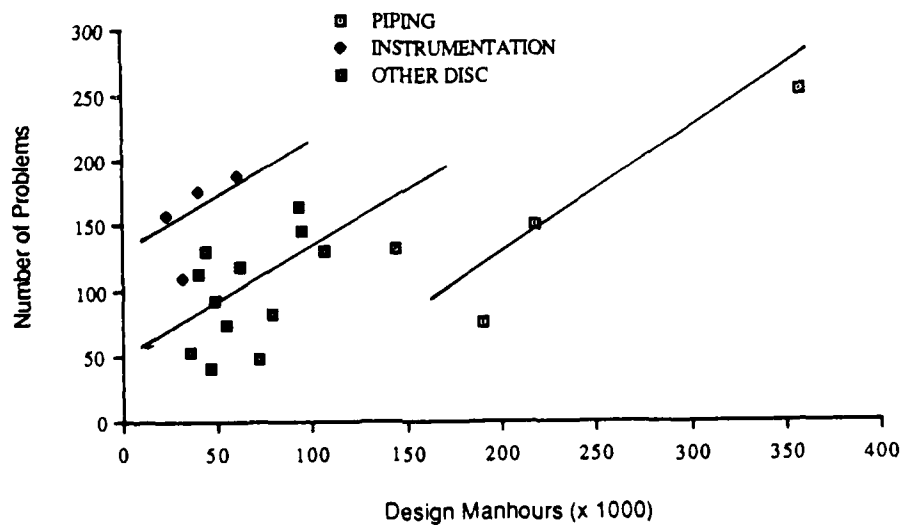


Figure 6.17 Plot of Problems versus Design Manhours (Categorized by Discipline)

three parallel lines--Piping, a combination of Civil, Equipment and Electrical, and Instrumentation (these lines are dashed-in). This subgrouping by disciplines was tested and the results are shown in Table 6.5 and Figure 6.18.

(Note: The dashed lines around the regression line represent the 95% confidence intervals for estimating the mean value of y (the closest dashed lines) and for predicting an individual value of y (the pair of dashed lines farthest away). Although each of the lines shown does have a confidence interval, only the confidence for the baseline disciplines are shown to avoid confusion.)

Table 6.5--Results of Regression Analysis for Number of Problems Using Design Manhours

Equation: $y = 51 + .8 \text{ MH} + C_{\text{Piping}} + C_{\text{Instr}}$

y = Number of Problems

MH = Design Manhours/1000

C_{Piping} = -70 (Constant used when predicting Piping Problems)

C_{Instr} = +78 (Constant used when predicting Instrument Problems)

$R^2 = 63\%$

Parameter	Estimate	T-Value	$T_{16,.025}$	$T_{16,.05}$
Intercept	51	3.16	2.12	1.75
Slope	0.8	3.89	2.12	1.75
C_{Piping}	-70	-1.87	2.12	1.75
C_{Instr}	+78	3.75	2.12	1.75

Test for model significance:

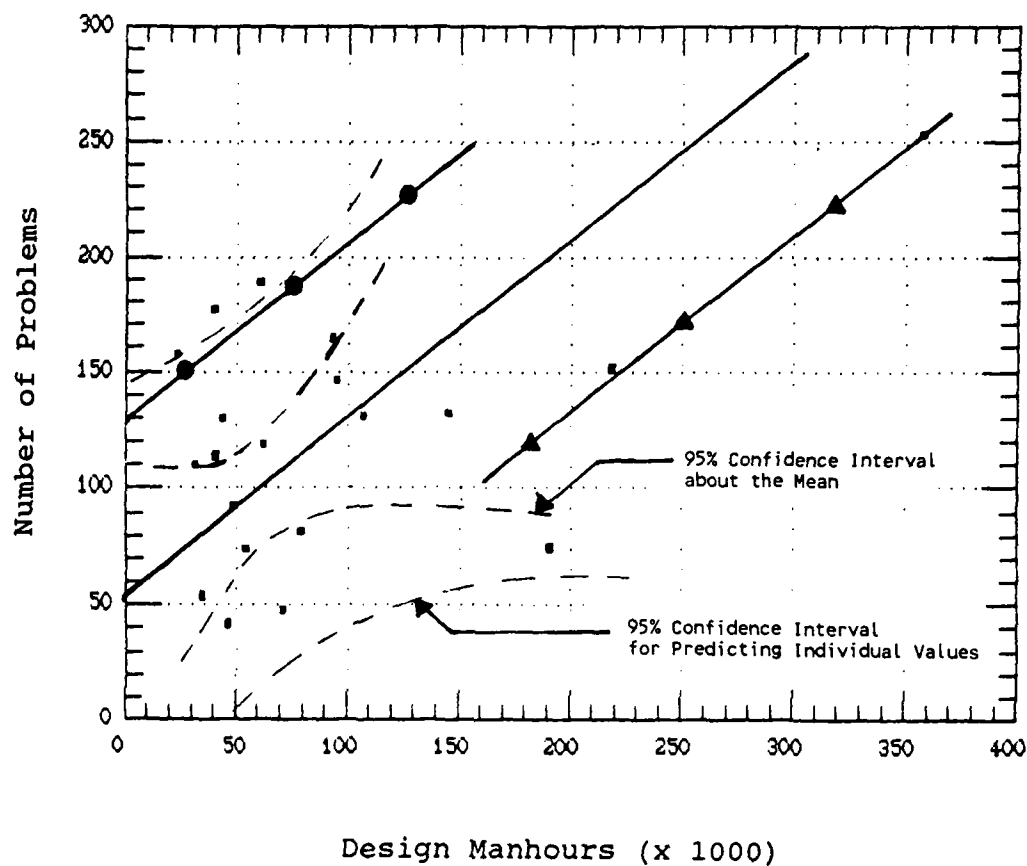
$F_{\text{Ratio}} = 9.12$ $F_{3,16,.05} = 3.24$

Test for model improvement by categorizing disciplines:

$F_{\text{Ratio}} = 16.6$ $F_{2,16,.05} = 3.63$

Conclusions:

1. Regression equation explains 63% of variability in manhours.
 2. Piping constant is significant at a confidence level of 90%, but not at 95%; however, do not drop from model since the data is limited and the trend should be researched further. All other variables are significant at confidence level of 95%.
 3. The model is significant.
 4. Subgrouping by Disciplines (Instrumentation, Piping, and the others) significantly improved the model.
-



Legend:

- Baseline
- - - Confidence Interval
- Instrumentation
- ▲ Piping

Figure 6.18 Graph of Regression Equation--
Forecasting Number of Problems Using
Design Manhours

Results show that there could indeed be three parallel equations used to predict the number of problems. An example to demonstrate the use of this regression equation to predict the number of design-related problems when the design manhours are known is:

Given: Piping Design Manhours = 350,000
 Instrumentation Design Manhours = 60,000
 Electrical Design Manhours = 90,000

Find: Predict the Number of Potential Problems for Each Discipline

Solution:

$$y = 51 + 0.8MH + C_1$$

A) Piping

$$y = 51 + 0.8(350,000/1000) + (-71)$$

$$y = 259$$

B) Instrumentation

$$y = 51 + 0.8(60,000/1000) + 78$$

$$y = 177$$

C) Electrical

$$y = 51 + 0.8(90,000/1000)$$

$$y = 123$$

Note: 1. The constant is applied only to Piping and Instrumentation.
 2. The confidence interval is approximately ± 90 .

This equation has an R^2 of 63% which means that design manhours explain 63% of the variability in the number of problems. It is felt that this equation can be used to approximate the number of problems expected in each discipline; however, it is recognized that the sample size is too small to accurately predict the number of problems. More research is needed to verify these findings. The expected result will be that disciplines with changes in technology such as Instrumentation will be on a parallel line above the baseline; however, as that technology matures, the discipline will return to the baseline. Piping will probably remain parallel but below the baseline simply because the larger design effort needed will show a reduced number of problems in relation to the other disciplines. The baseline would include all disciplines that have known technologies. It is felt that at this simple level of modelling, the results are acceptable as a basis for predictions at this time and to serve as a guide for further research.

6.3.3 Forecasting Using Construction Manhours

The next method of predicting the number of problems uses the construction manhours as the inde-

pendent variable. Table 6.6 shows the construction manhours for each discipline. Figure 6.19 shows a plot of the number of problems versus the number of construction manhours for each discipline. Unlike the plot with the design manhours where trends due to complexity can be seen, no discernible pattern can be ascertained in this plot. This is not unexpected since the design-related problems do not appear to be a function of complexity during the construction phase of a project; however, there appears to be a relationship between the number of problems and construction manhours.

Table 6.6--Construction Manhours for Each Discipline
(x 1000)

Discipline	H-Oil	HGU	VPS	SRU
Civil	272	134	245	245
Structural	69	37	50	36
Equipment	152	64	45	89
Piping	594	304	419	367
Electrical	282	142	179	164
Instrumentation	287	157	168	121

Complexity trends among the units were investigated without any significant results. However, as in the case of design manhours, Figure 6.20 shows two parallel lines when investigating the influence of the different design groups on the number of problems. Once again, the disciplines were subgrouped. The baseline group includes all disciplines except Instrumentation which appears parallel to it. The model was tested and the results shown in Table 6.7 and Figure 6.21.

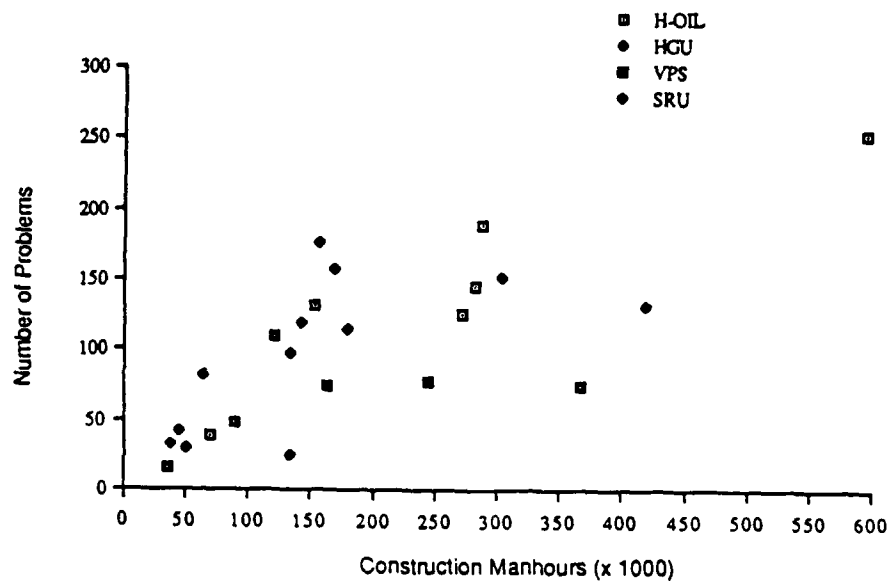


Figure 6.19 Plot of Problems versus Construction Manhours (Categorized by Unit)

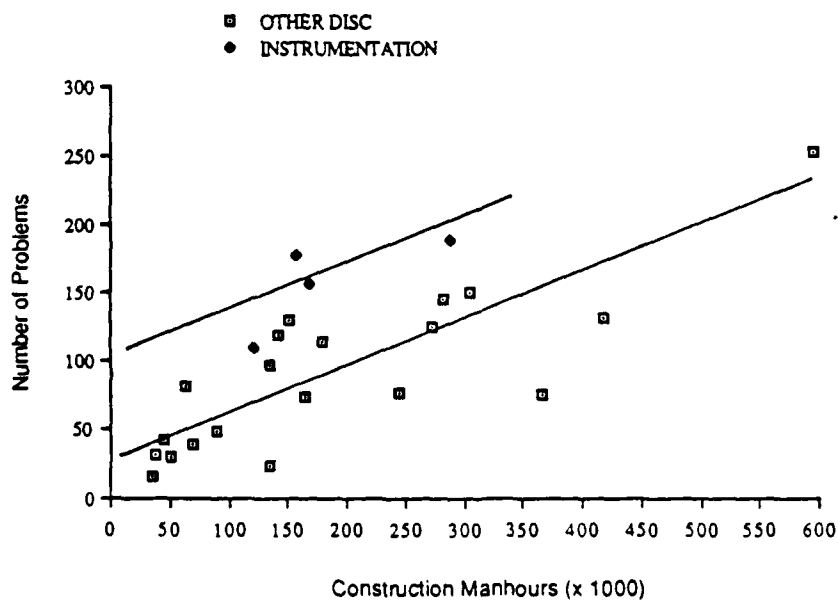


Figure 6.20 Plot of Problems versus Construction Manhours (Categorized by Discipline)

Table 6.7--Results of Regression Analysis for Number of Problems Using Construction Manhours

Equation: $y = 29 + .3MH + C_{Instr}$

y = Number of Problems

MH = Construction Manhours/1000

C_{Instr} = +70 (Constant used when predicting Instrument Problems)

$R^2 = 74\%$

Parameter	Estimate	T-Value	$T_{21,.025}$
Intercept	29	2.48	2.08
Slope	0.3	6.60	2.08
C_{Instr}	+70	3.94	2.08

Test for model significance:

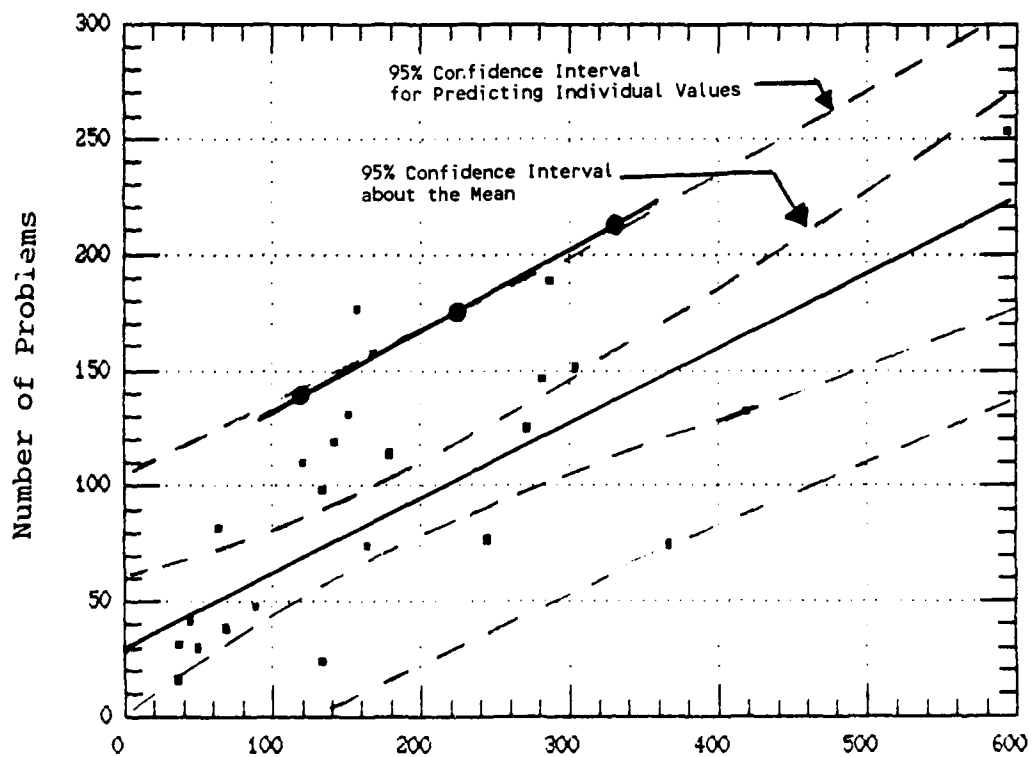
$$F_{Ratio} = 29.13 \quad F_{2,21,.05} = 3.47$$

Test for model improvement by categorizing disciplines:

$$F_{Ratio} = 15.5 \quad F_{1,21,.05} = 4.32$$

Conclusions:

1. Regression equation explains 74% of variability in manhours.
 2. All variables are significant at a confidence level of 95%.
 3. The model is significant.
 4. Subgrouping by Disciplines (Instrumentation and the others) significantly improved the model.
-



Legend:

- Baseline
- - - Confidence Interval
- Instrumentation

Figure 6.21 Graph of Regression Equation--
Forecasting Number of Problems Using
Construction Manhours

An example of how to use the regression equation to predict the number of design-related problems when construction manhours are known is:

Given: Piping Construction Manhours = 550,000
Instrumentation Cons. Manhours = 300,000

Find: Predict the Number of Potential Piping and Instrumentation Problems

Solution:

$$y = 29 + 0.3MH + C_{Instr}$$

A) Piping

$$y = 29 + 0.3(550,000/1000)$$
$$y = 194$$

B) Instrumentation

$$y = 29 + 0.3(300,000/1000) + 70$$
$$y = 189$$

Note: 1. The constant is added when predicting potential Instrumentation problems.
2. The confidence interval is approximately ± 70 .

The R^2 for this equation is 73%, which means that the construction manhours explain 73% of the variability in predicting the number of problems. Reviewing this model and the previous forecasting model, the question arises whether or not these equations are realistic.

It must be remembered that this data set is very limited. The Instrumentation discipline has four data points, while the baseline contains only twenty

data points. Nevertheless, the trend is there and early predictions can be approximated using these equations. Further research must be done to validate this model.

Another criticism is the fact that the intercept is not zero which implies that problems exist without any work being done. It must be remembered that regression provides a best-fit line by minimizing the least squares of the residuals which often includes an intercept. The belief is that the intercept will decrease to zero with a larger data set; however, in order to provide as accurate an estimate as possible within the limits of the data, the regression equations are recommended for initial use.

The method of increasing the constant to account for Instrumentation is a perfect example of logically accounting for a change in technology. Once again, as the technology becomes more familiar to the designer, the constant will decrease until the discipline is included in the baseline.

6.3.4 Forecasting Using Progress Schedules

The first two methods of forecasting the number of problems can be used in the feasibility and design stages of a project to get an idea of the num-

ber of design-related problems that can be expected in the construction phase of the project. The question then arises as to whether or not a method is available to predict the number of problems that can be expected once a project is under way. Therefore, the final method of predicting the number of problems will be by examining each discipline's progress schedule.

It can be observed from the graphs in Chapter 5 that the cumulative number of problems and the percentage of problems for each discipline followed the same pattern over the construction period for each unit. Therefore, regression analysis is used to analyze the relationship between problems and construction progress.

Regression equations were developed on this project to see if all four units displayed the same trends over the construction phase of the project. The variables for the analysis were:

Independent variable: Percentage Construction
Complete

Dependent variable: Percentage of Problems

Linear regression was used to analyze Total Problems and all major disciplines--Civil, Structural, Equipment, Piping, and Electrical. Although the data for some disciplines such as Civil, Equipment, and

Instrumentation do not appear to have linear trends, the linear model was used for this study for the following reasons:

1. The data for this initial study of design-related problems was limited to one mega project with four separate units, so complicated models and curve-fitting are not appropriate at this time.
2. Each discipline's schedule can be approximated by a line throughout most of the discipline's progress. The Civil discipline will be analyzed from 0-90% complete, Equipment from 0-100%, and Instrumentation from 35-100% complete.

One of the major assumptions when using regression analysis is that the data are independent. To develop this model, the data are cumulative problems which means that each point is dependent upon the previous value. This introduces autocorrelation into the model and invalidates the R^2 -value and the F-value. This means that these equations cannot be used in hypothesis testing; however, the equations can still be used to forecast future problems, which is the purpose of this model.

Table 6.8 shows the results of the regression analysis. The table shows the discipline, the regression equation for the problems, and regression equation for the construction schedule for each

discipline. (Note: The best-fit lines are shown in Figures 6.22 thru 6.28. Once again, the 95% confidence levels are shown for predicting the mean value of y (the closest pair of dashed lines to the regression line) and for estimating the value for another point.)

Table 6.8--Results from Regression Analysis Using
Percentage of Project Complete

Discipline	Equation (Equation for Construction Schedule)
Total Problems	$y = -0.8 + 0.9x$
Civil	$y = 28 + 2x$ ($y = 1 + 2.5x$)
Structural	$y = 0.3 + 1.0x$ ($y = 3.6 + 1.3x$)
Equipment	$y = -0.9 + 0.6x$ ($y = 4 + 1.1x$)
Piping	$y = -7.2 + 1.0x$ ($y = -6.3 + 1.1x$)
Electrical	$y = -4.8 + 1.0x$ ($y = 0.6 + 1.0x$)
Instrumentation	$y = -69 + 1.6x$ ($y = -44 + 1.4x$)

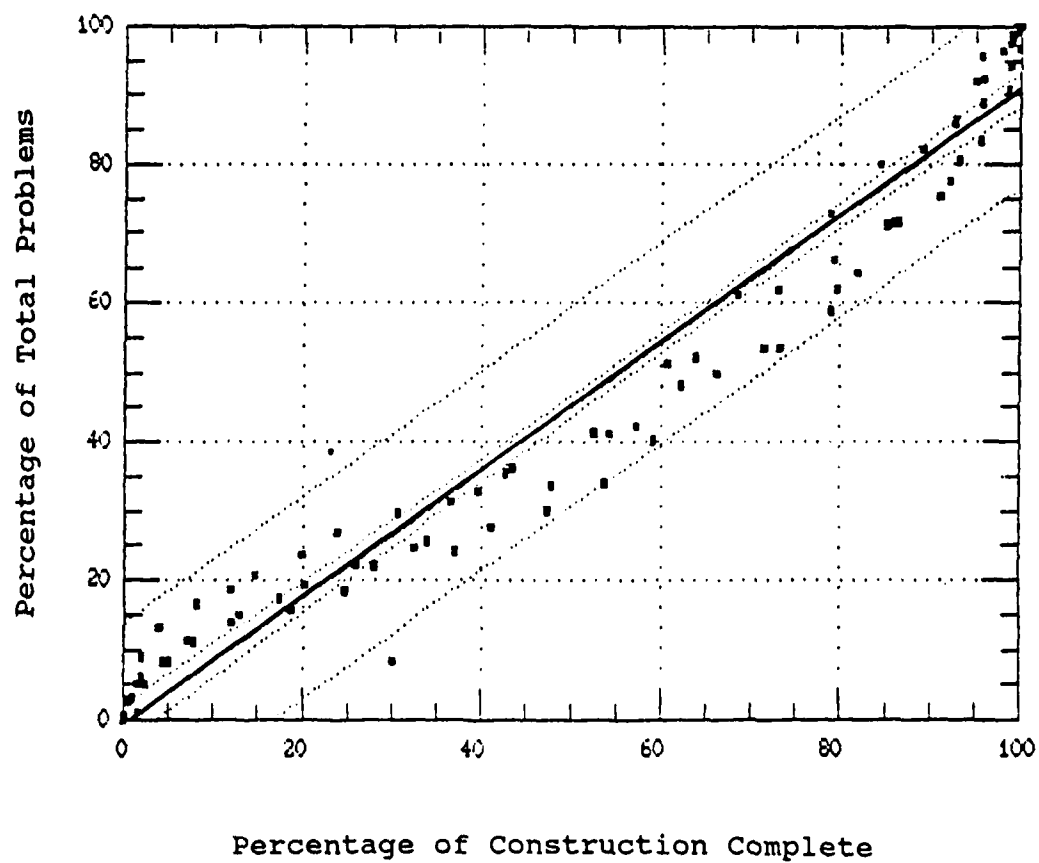


Figure 6.22 Graph of Regression Equation--Total Problems

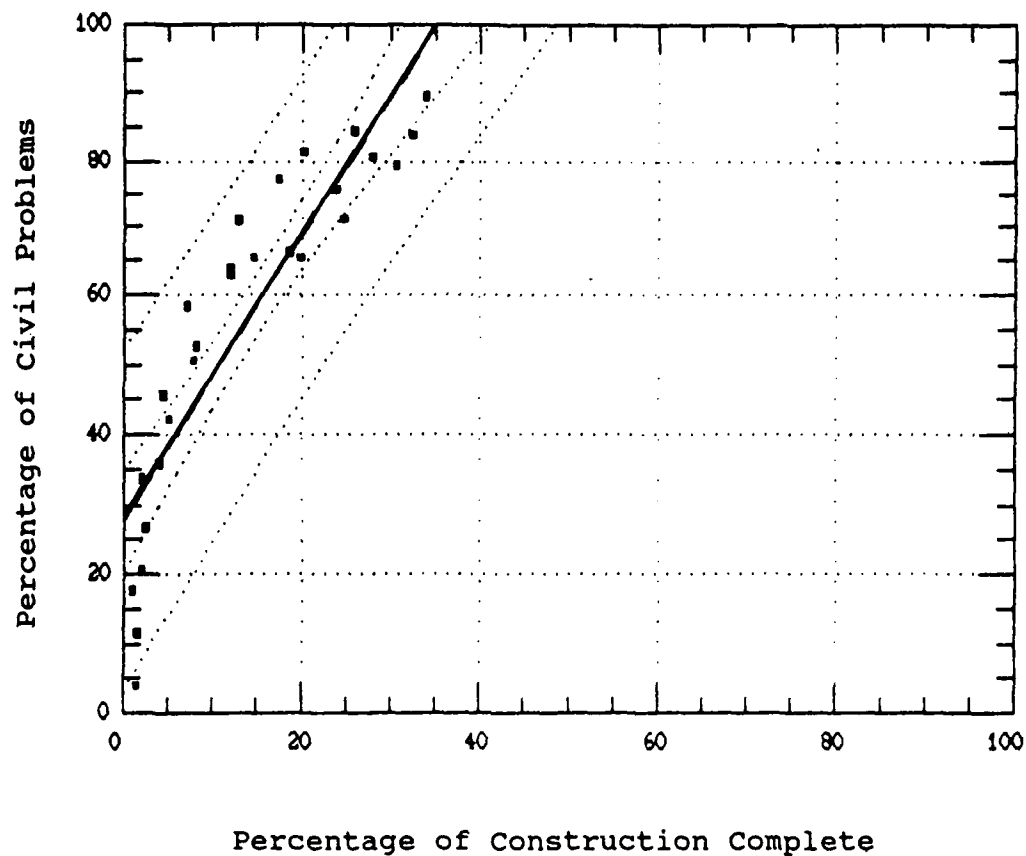


Figure 6.23 Graph of Regression Equation--Civil Problems

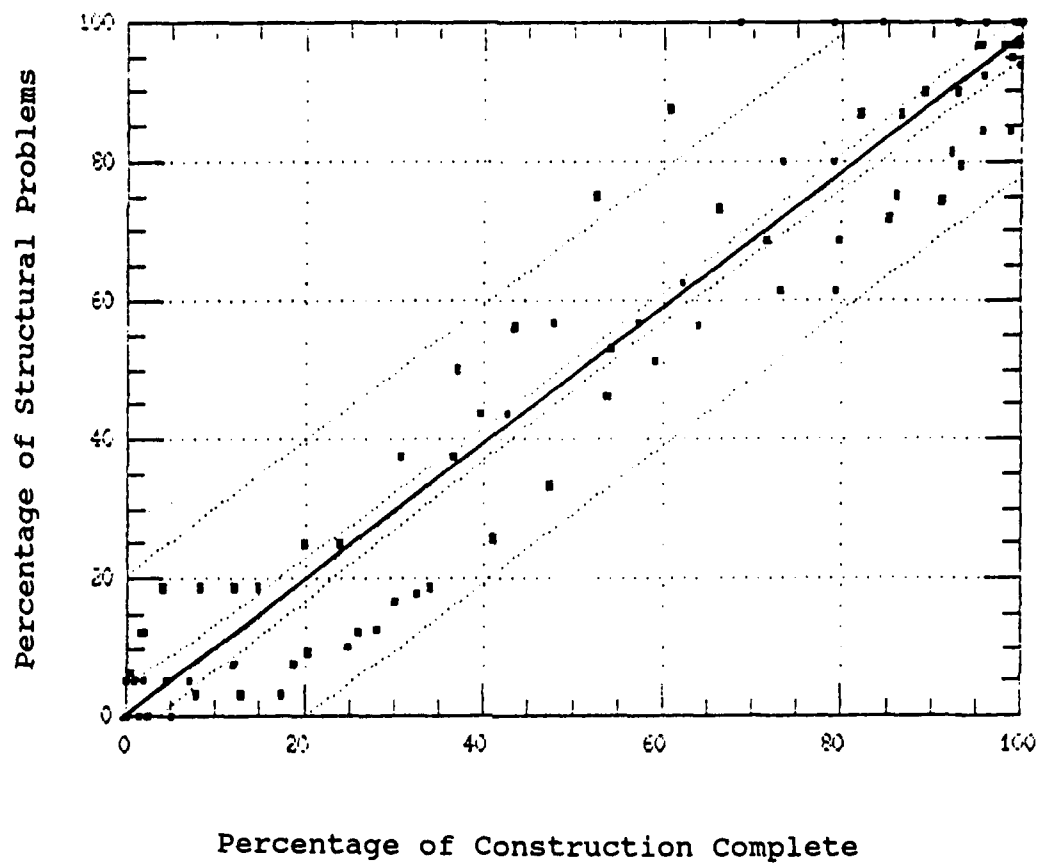


Figure 6.24 Graph of Regression Equation--Structural Problems

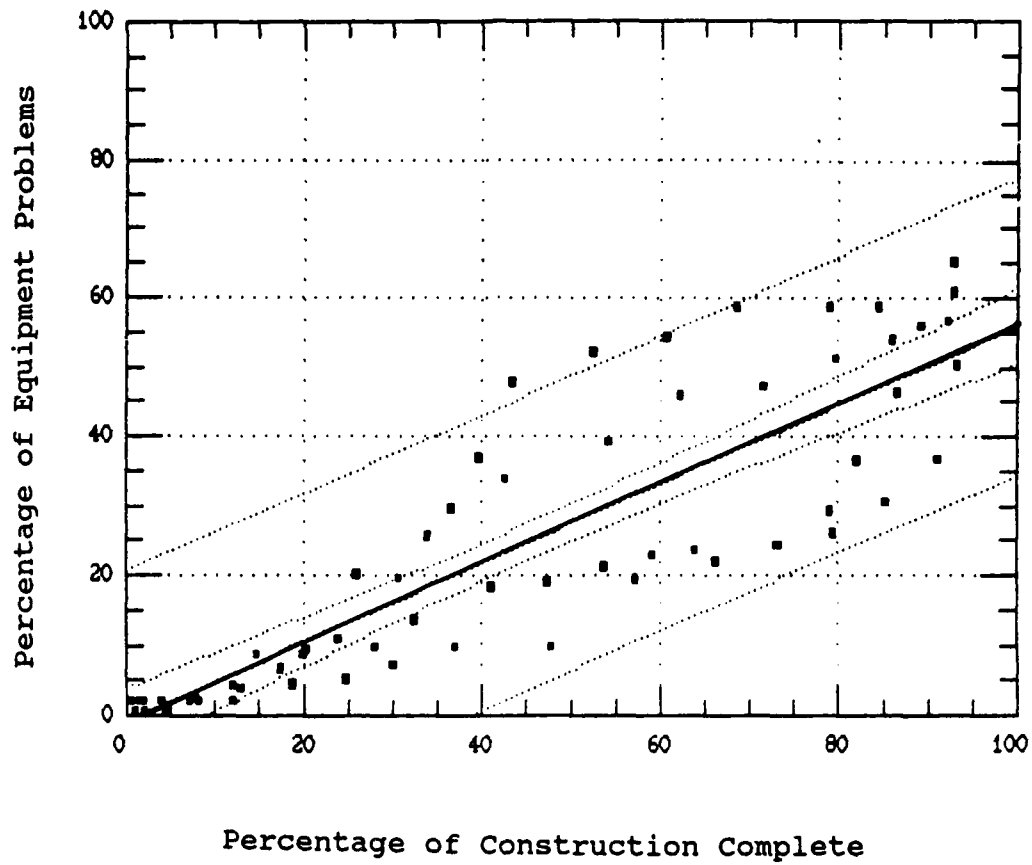


Figure 6.25 Graph of Regression Equation--Equipment Problems

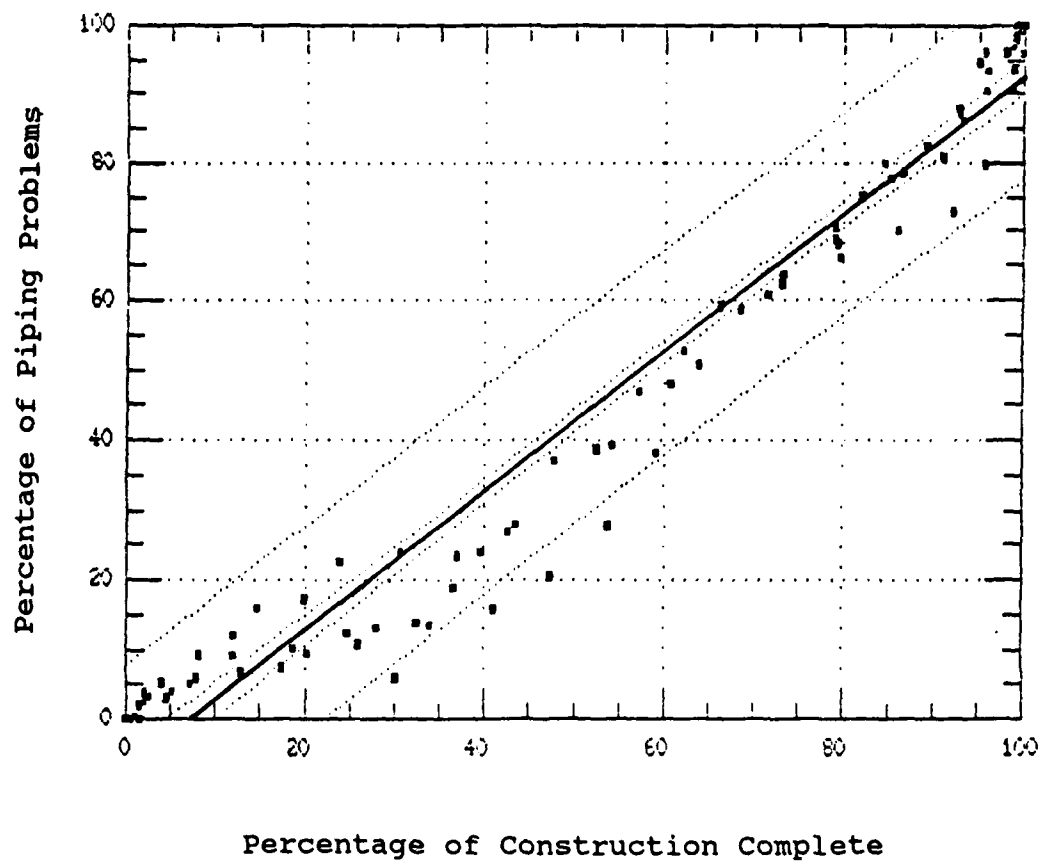


Figure 6.26 Graph of Regression Equation--Piping Problems

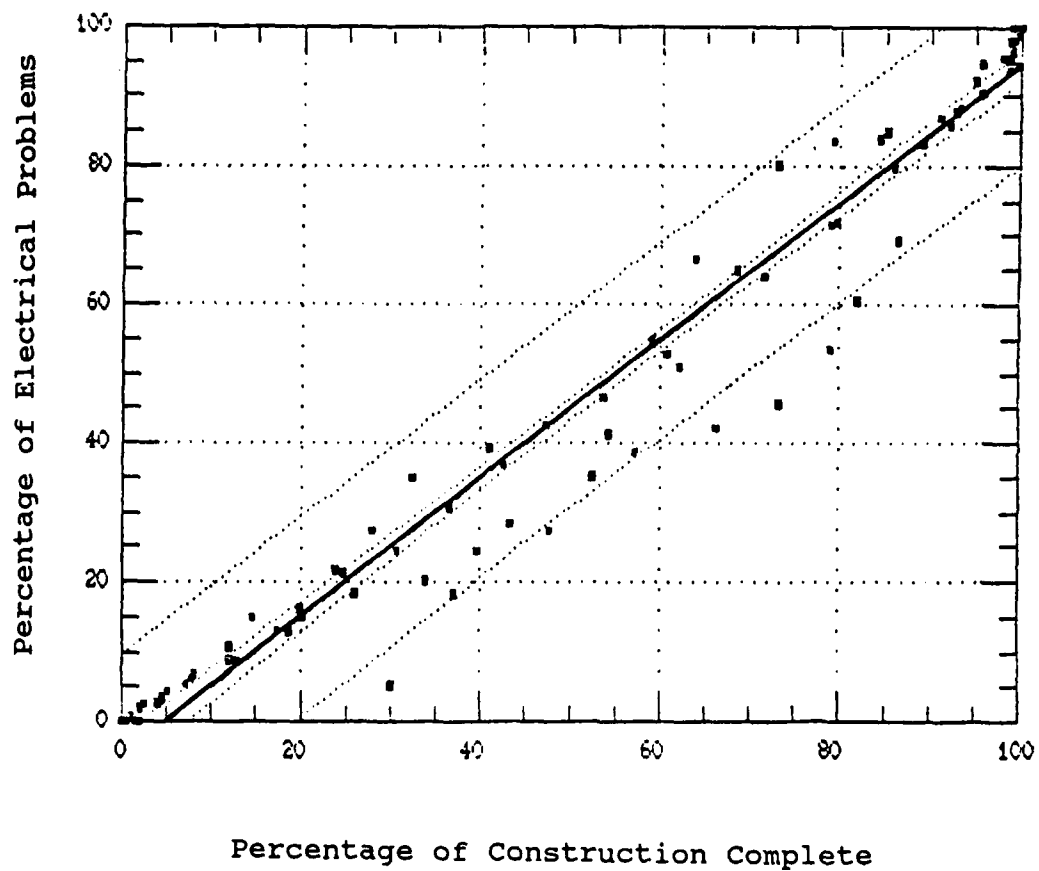


Figure 6.27 Graph of Regression Equation--Electrical Problems

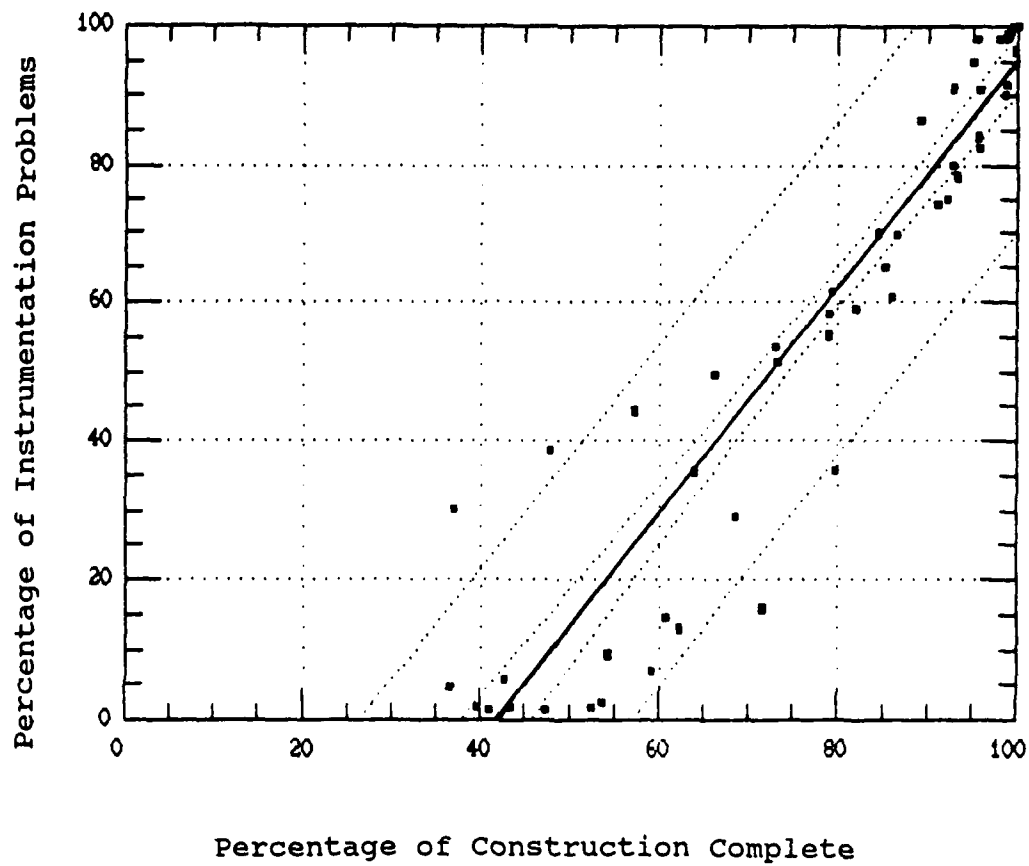


Figure 6.28 Graph of Regression Equation--
Instrumentation Problems

The results are as expected--the regression lines show slopes of almost one for most disciplines. This was shown and discussed in the Problem Deviations section. The high-intercept values, such as 28 for Civil and -69 for Instrumentation, are for those disciplines which had deviations from the Profile B curve where a linear model is probably not the best choice.

The most significant result from the regression analysis is that it shows that there is a relationship between the number of problems and the construction progress for each discipline. It must be remembered that the regression does not show a cause-effect relationship. In this case, it is obvious that an increase in construction progress does not in itself cause an increase in the number of problems. However, the number of problems can be predicted from these equations. The equations in Table 6.8 are in percentages, and calculations would have to be done to get the predicted number of problems from a known number of problems at a certain stage of construction. It is assumed that instead of using the memos only for communicating problems, management will have an individual responsible to classify the memos according to the suggested categories and summarize this data

throughout the project. If so, the actual number of problems at any point of time would be known. For example, at 20% construction complete, 27 piping problems were recorded and will be used in the following example.

Given: H-Oil Unit
20% complete
Actual number of problems recorded: 27

Find: Predict the number of problems at the end of construction

Solution:

$$\begin{aligned}y &= -7.2 + 1.0x \\y &= -7.2 + 1.0(20) \\y &= 12.8\end{aligned}$$

This means that 12.8% of the Piping problems have occurred at 20% construction complete.

The same equation is used to predict the value at 100%. With this equation, $y = 92.8$. (Note: The value does not equal 100% as expected since the equation was developed from the piping data recorded throughout the construction phase using linear regression. This line (shown in Figure 6.26) does not intercept 100% for piping problems when the project is at 100%.)

$$\begin{aligned}y &= -7.2 + 1.0(100) \\y &= 92.8\end{aligned}$$

To find the predicted number of problems, a ratio can be set-up between the number of problems at 20% construction complete and 100% construction complete:

$$\frac{n}{92.8} = \frac{27}{12.8}$$

$$n = 196 \pm 90 \text{ @ } 100\% \text{ construction complete}$$

The predicted value at the end of the project is 196. The actual result from the H-Oil unit for the piping discipline is 253, which is within the 95% confidence interval. In this case, the model underestimated the actual number of problems, but it gave a good indication of the number of problems that could arise without management action.

This example shows the potential uses for regression analysis, but it must be remembered that the equations are developed from the four units of one mega project in the industrial sector. Without further research and more data, it is not possible to say that these equations are correct throughout the industry or even for another project. In fact, the equations would more than likely be different, but this study shows the units do appear to have the same trends and further research in this area should be done.

What equation can be used to predict problems if the units are still under construction and the regression equations are not yet developed? To answer this, a look back at the graphs in Chapter 5 is necessary. It can be observed that the curve for each discipline's actual progress parallels the percentage

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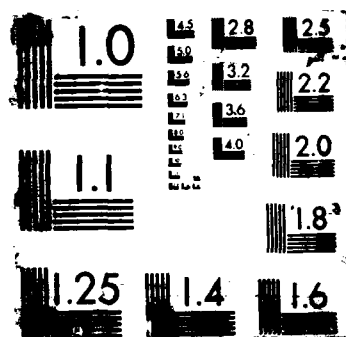
ANALYSIS OF DESIGN-RELATED PROBLEMS FROM AN INDUSTRIAL
PROJECT(U) AIR FORCE INST OF TECH WRIGHT-PATTERSON AFB
OH J R GLAVAN MAY 88 AFIT/CI/NR-88-122

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of problems curve for each unit. Since the two curves are parallel, a regression equation was developed for each discipline's progress curve. This is shown in parenthesis below the regression equation for each discipline's percentage of problems in Table 6.8. In Table 6.9, the equation for the percentage of problems (labeled Regr) is compared to the equation for the discipline's progress (labeled Sched) for Piping, Electrical and Instrumentation disciplines.

Table 6.9--Comparison of Results of the Regression Equations for Progress Schedule and Percentage of Problems

Project Progress (%)	Piping Sched (%)	Regr (%)	Electrical Sched (%)	Regr (%)	Instrument Sched (%)	Regr (%)
10	5	3	11	5	*	*
20	16	13	21	15	*	*
40	38	33	41	35	12	*
60	60	53	61	55	40	27
80	82	73	81	75	68	59
100	104	93	101	95	96	91

* Predicted percentage less than zero

Note: The results in this table are the predicted percentage of problems that would occur for a particular discipline.

In Table 6.9, the predicted percentage of problems calculated by using the discipline's progress is higher than the predicted value from the regression equation for each discipline. That would translate into predicting less problems than expected. This could introduce a false sense of security in management that the problems are not too bad, or it may show the trend and alert management to take preventive action.

Further study reveals that in the interval between 20 to 80% construction progress, the two values are within 15% of each other. This is the area that would be the most helpful in predicting the results at the end of the project. Therefore, using the regression equation for a discipline's progress will not introduce much error--at least for the purpose of estimating the number of problems.

Using this information, combined with the observation of increasing problems at the end of the project as well as actual experience, the discipline's scheduled progress equation could be used as a predictor with the interpretation that the predicted number of problems will probably be a minimum that could

quickly escalate if management does not take preventive measures.

6.3.5 Summary of Forecasting Models

Several forecasting models were investigated to not only provide an explanation of when and why certain problems occurred, but to be used to help future project planners predict the number of problems for each construction discipline.

Time series analysis did not work very well for this project. The random walk series of problems, the uneven time interval for activity progress, and the relatively short duration of the construction project were three critical factors which prevented successful utilization of this technique.

The remaining forecasting models utilized regression analysis. For future projects, the number of problems can be predicted using either design manhours or construction manhours. The models did not explain all the variability in the number of problems, but they do show trends and can give management an indication of the potential problems that could occur.

For projects under way, the proposed method of predicting the number of problems using the disci-

pline's progress schedule shows a strong correlation to the actual results shown in Chapter 5. This equation usually underestimated the number of problems which were documented by the end of the project, but it definitely established the trend and is fairly accurate in the 20 to 80% construction complete range.

6.4 Problem Economics

Previously, the design-related problems were categorized and the timing of these problems was examined for patterns or trends that could be useful for forecasting future problems, but the missing parameter that is needed by industry is the economic impact of these problems and the cost of possible solutions to (1) prevent these types of problems from recurring or (2) minimize their impact.

Currently, industry has not been able to determine the exact cost of problems, but studies are under way (see CII Quality Task Force). Unfortunately, the Inter-Office Memos did not provide an estimate of the cost, time or the degree of impact that the problem had on the project. However, in Appendix B, an attempt is made to approximate the cost of rework problems and examine potential solutions.

Why quantify these rework costs? The answer lies in the fact that currently there are no data available to justify the cost of implementing systems to prevent future problems. Some systems such as Computer-Aided Design (CAD) are touted as providing savings of approximately 10% of a project's costs, but the implementation costs are high and must be justified.

A modified IOM form which includes economic data could be used to establish actual rework costs. The potential savings from these problems could be used to offset the costs of installing a system. For example, using approximate estimating techniques, a savings of at least \$800,000 in rework labor costs alone could have resulted through the adoption of CAD on this project (see Appendix B).

Although the IOM's from this project could not be used to document the economic impact of these problems, the study and discussion in Appendix B show a methodology that can use a modified IOM form to document the construction costs associated with that rework and ultimately used to justify the costs for systems that can eliminate these problems.

6.5 Summary

The design-related problems were analyzed in this chapter to determine the cause of problems. The results showed that process and design complexity are one of the causes of design-related problems. Construction techniques were similar for all four units and, therefore, did not play a major part in determining the number of problems.

Contingency tables established that problem categories were not independent of organization or discipline of origination. The results confirmed specific relationships (such as Drawing problems being originated by the construction contractor) that can be helpful to management in planning future projects.

Profile curves that tested whether the percentage of problems is linearly proportional to the percentage of discipline's progress complete proved the most insightful. These curves showed when problems occurred for each discipline and by examining the procedures and characteristics of each discipline, plausible reasons for the timing of these problems were proposed. These profile curves show management when particular disciplines have problems and will enable them to take corrective action.

Three methods of forecasting future problems were proposed. It was observed that the number of problems had a strong relationship to the design and construction manhours and models were developed for each of these relationships. The equations can be used to predict future problems on projects of similar nature. The third method to forecast the potential number of problems used the discipline's progress schedule. This method could be used to predict problems for an ongoing project. Although the data are limited, definite trends can be observed and further research using these procedures is recommended.

The final section discusses the use of the IOM's as a method for measuring the economic impact of rework. A potential method of calculating the cost of problems, as discussed in Appendix B, estimates that rework labor costs of approximately \$800,000 could be eliminated through the use of CAD.

CHAPTER 7

CONCLUSION

It is helpful to review the purpose of this study before examining the conclusions that can be drawn from the effort. The purpose was to examine existing documentation from a completed industrial project to identify and analyze the design-related problems that occurred in the construction phase of the project.

This effort was one of the first of many studies needed to link the problems discovered in the construction phase of a project to the causes of the problems which originate in the design phase.

The objectives used to support this purpose are:

1. Identify and categorize design-related problems through existing documentation.
2. Examine data for specific relationships and trends. Determine if the type and timing of design-related problems are consistent or dependent upon the process technology. Establish the discipline and organization of the originator.
3. Establish profile curves to examine when problems are discovered by each discipline and explain why these problems occur.

4. Using discovered relationships and trends, explore methods for predicting potential problems on future projects by developing forecasting models.

7.1 Conclusions

This dissertation utilized existing documentation to examine a completed project. Of particular interest was the design-related problems that occurred during the construction phase of the project. From this study, the following conclusions can be drawn:

1. Significant Item Lists (SIL) are helpful in identifying potential problems that can occur throughout the design and construction phase of a project.
2. Information in the SIL is too general to be used for detailed analysis of design-related problems that occur during the construction phase. A SIL does not provide the link between a problem in construction and the cause which usually originates in the design phase.
3. Design-related problems can be identified by using a form similar to the Inter-Office Memo. This documentation can provide the link between problems in construction and the design phase of the project. Once this link is established, the causes of these problems can be investigated.
4. Design-related problems can be identified and classified into eight categories:

Scope, Design, Drawings, Procurement,
Specifications, Schedule, Construction,
and Quality Assurance/Quality Control.

5. The types and percentage of problems identified by the IOM's were relatively consistent throughout the life of each unit. This was due to the fact that the problems are a function of process and design complexity. Since the project was fast-tracked and the problems originated in the design phase, there was no chance of feedback from the construction of one unit to modify the design procedures for the other units.
6. All categories showed an increase in the percentage of problems in the last 20% of the construction schedule. This is due to the current practice of testing complete systems instead of individual pieces of equipment and the last minute changes needed to safely and efficiently operate the entire unit. Some of these problems cannot be eliminated, but others should be discovered or eliminated earlier through better quality control and testing of individual pieces of equipment.
7. The largest number of documented design-related construction problems involved drawings. This category accounted for 28% of the problems. Most of these could be eliminated today through the use of CAD.
8. Instrumentation and Piping disciplines accounted for 52% of the problems. The results of Piping are not unexpected, but Instrumentation represented approximately 13% of the work effort and was not expected to have that many problems. The change in instrumentation technology accounted for this result and must closely be watched in the future.
9. Contingency tables showed that the problem categories were not independent of organization or discipline of origination. Owners and designers should try to reduce the number of problems being originated by the constructor. Examples would include the Drawing and Specification problems that were discovered by the constructor.

10. Time series analysis does not appear to be an appropriate analytical tool for design-related problems. Random problems, length of construction, and irregular intervals between problems were three factors that made time series analysis difficult to perform.
11. Profile curves, labeled A (convex), B (straight line), and C (concave), were developed to test the hypothesis that the percentage of problems are linearly proportional to the percentage of discipline progress complete. The results showed that Piping and Electrical did vary linearly (Profile B), Civil problems occurred very early (Profile A), while Structural, Equipment and Instrumentation problems occurred late in these disciplines' schedules (Profile C).
12. Disciplines that follow Profile C (concave) pose the biggest challenge to management since these problems cannot be predicted from the earlier problems. Methods must be introduced to change this type of curve to a Profile B (straight line). An example would be improving the quality control procedures or implementing new testing methods for Equipment.
13. Models using design manhours and construction manhours were developed to predict the number of problems for each discipline. Trends indicate that a change in a discipline's technology will increase the number of design-related problems associated with that discipline. The equations are:

$$\text{Number of Problems} = 51 + 0.8(\text{Design Manhours}/1000) + C_1$$

$$C_1 = \begin{array}{l} -70 \text{ for Piping} \\ +78 \text{ for Instrumentation} \end{array}$$

-OR-

Number of Problems =

$$29 + 0.3(\text{Construction Manhours}/1000) + C_1$$

$$C_1 = +70 \text{ for Instrumentation}$$

Confidence interval is approximately ± 90

14. For projects in progress, a forecasting model to predict the number of problems was developed using each discipline's progress curve. An example for Piping is:

Percentage of Piping Problems =

$$-7.2 + 1.0 (\% \text{ of Construction Complete})$$

15. Although the documentation did not provide exact numbers, estimates showed that implementation of CAD could eliminate 25% of the problems found in this study. This represents approximately \$800,000 of the rework direct labor costs.

7.2 Recommendations

This study had an ideal situation in that one mega project could be broken into four different units with varying degrees of process technology ranging from the mature technology of the VPS to the newest technology of the H-Oil unit. The similarities and differences among the units could be studied and various trends recognized. This project proved useful in demonstrating that design-related problems can be tracked through existing documentation. However, since the data were limited, more projects are needed to verify the findings. Therefore, the following recommendations are made:

1. The causes of design-related problems originate during the design phase of a project. The IOM's with the slight modifications previously mentioned, identify the problems and can be used as a link to trace the problems back to the design phase. Therefore, the recommendation is to use the IOM's to identify design-related problems and trace them back to the design phase to determine the cause of the problem. This must be done for an ongoing project to actually discover the causes. Concentration should initially be on various industrial projects to determine if the relationships found here exist throughout this sector of the construction industry.

2. Historical data are important for successful completion of future projects. Currently, there is a lack of data. Information on design-related problems should be recorded on standard forms, entered into a common database, and disseminated throughout the industry. This could be done through an organization such as the Construction Industry Institute.
3. Claims have been made that CAD saves money on the design and construction of a project. Currently, it is hard to find economic justification for design savings, but the IOM's can be used to identify the problems that could be eliminated from the construction phase of the project. The savings from this area alone can justify the costs of a CAD system. Therefore, a recommendation is made to modify the existing memo form so that economic cost data can be estimated or the actual cost to correct the problem recorded.
4. The start-up phase of a project is critical to the success of a project, yet it has not been examined in great detail. This study showed that design-related problems increased during the last 20% of construction; therefore, it is recommended that a detailed study should be undertaken to determine the testing procedures, quality control, and management policies that are in effect at that time.
5. Profile curves should be reviewed for each discipline. Equipment and Instrumentation design and construction procedures should be studied to determine if the number of problems can be reduced at the end of the project. Quality control and testing procedures should be reviewed.

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APPENDICES

APPENDIX A

SUMMARY OF EARLIER STUDIES

During the life of this project, University of Texas graduate students completed sixteen studies. Topics ranged from organizational communication to documentation of start-up problems. This appendix lists the reports and provides a brief description of their contents.

1. A Study of Organizational Behavior
by E.D. Greenwood
August, 1982

This report identifies problem areas in the communication network and develops approaches to solve these problems. Communication Improvement Circles, Engineering Delay Surveys, and Design Delay Surveys were used to identify potential problem areas. Results and solution techniques are presented.

2. Project Activity Flow Diagrams
by J.T. O'Connor
September, 1982

This report details the mechanism for formally relating the various project activities that must occur for a project's successful completion. Each phase of the project is broken down into activities, jobs and tasks. The diagrams can be used to show organizational responsibility, flag critical items for each group, and establish the framework for project communication.

3. Engineering Design Survey
by T.F. Como, J.D. Borcharding, and R.L. Tucker
August, 1983

This report examines the major engineering design activities within the design contractor's office. The purpose of the report is to document and evaluate the delays encountered in the design and engineering of Estimate 7640. It provides a Procedural Manual (methodology, recommendations, conclusions) for conducting future Design Delay Surveys.

4. An Assessment of the Potential Problems Occurring in the Engineering Phase of an Industrial Project
by M.A. Smith and R.L. Tucker
August, 1983

This report collects and quantitatively evaluates the factors that have causal relationships to numerous significant problems occurring on a large, industrial project. The results are presented in Impact/Controllability matrices which relate influence factor causality and controllability to specific problem areas.

5. Data Collection Methods for Constructability Improvement Ideas
by M.A. Larimore and R.L. Tucker
December, 1983

A constructability program seeks to reduce excessive construction labor costs by modifying project designs to allow more efficient construction practices.

This report includes the methodologies, results, analysis, and conclusions on the process of collecting constructability ideas in a ten-month study (9/1/82 -- 6/30/83).

6. Improving Industrial Project Constructability
by J.T. O'Connor and R.L. Tucker
December, 1983

The causes, characteristics, and consequences of industrial project constructability problems and solutions are investigated. This report details methodologies, how to collect ideas, analysis of results, causes and costs, and strategies for future projects.

7. Constructability Improvement Ideas
by J.T. O'Connor
December, 1983

This report is a compilation of the 335 constructability ideas suggested during the early stages of the project. It is organized by work category.

8. The Development of a Field Inspection Manual for Texaco Field Inspectors
by L.M. Hanrahan
January, 1984

This report discusses the need for and development of a Field Inspection Manual. The manual is an instructional aid to field personnel assigned to new projects and a guide for field personnel onsite in performing their daily/periodic inspection duties. It should serve as a foundation for a Texaco Quality Control Manual.

9. Time-Lapse Photography Case Study: Electrical Cable-Pull Operations
by S.W. Summey
January, 1984

This report shows the results of a time-lapse study. It describes the work flow and the crew balance. Recommendations to improve the cable-pulling operations are made.

10. User's Manual: Time-Lapse Photography for Construction Operations Research
by S.W. Summey with additions by R.S. Mayer
January, 1984

This report develops standards and methods for Time-Lapse Photography programs on large, industrial construction projects. It discusses data collection, data reduction, data analysis and evaluation, and data presentation.

11. Productivity Measurement Systems in the Piping Craft of an Industrial Project
by R.D. Cantwell and R.L. Tucker
May, 1984

This report discusses the information a productivity measurement system must provide to the management staff on a large industrial project by using the piping craft as an example. It also discusses the need for a common standard of productivity measurement for the construction industry for the various crafts.

12. Characteristics Which are Productivity Differentiators Among Construction Foremen
by G.J. Lemna, J.D. Borcharding, and R.L. Tucker
December, 1984

This report identifies ways in which highly productive foremen perceive or perform their jobs. The report describes the method of data collection, the analysis, and the results of the study.

13. Material Management on Industrial Construction Projects
by K.M. Kirn
December, 1984

This handbook describes the complex Material Management System of a large refinery expansion project. It discusses the overall system activities, the interface between the various project groups, and individual responsibilities and functions. This handbook can help prevent the duplication of effort or the omission of required actions that sometimes occurs on large projects.

14. Time-Lapse Technologies: A Comparative Study for Construction Operations Research
by R.S. Mayer
May, 1985

This report discusses the potential use of time-lapse videotape. The advantages and disadvantages of both videotape and super-eight time-lapse systems are discussed. The report compares equipment, costs, methods, and the results obtained from using each system.

15. Evaluation and Analysis of Constructability Improvement Ideas
by J.H. Glanville and J.T. O'Connor
December, 1985

This report continues the constructability efforts of Larimore and O'Connor. It develops a method to rate ideas and introduces a categorization scheme based on the common characteristics of the ideas. 371 constructability ideas were introduced during this part of the study.

16. Investigation of Start-Up Problems
by J.R. Glavan and R.L. Tucker
January, 1986

This report documents the problems encountered during start-up. It lists the problems, the magnitude of each problem, the phase of the project where the problem originated, and the organization which controlled the decision which led to the problem.

APPENDIX B

ECONOMIC IMPACT OF DESIGN-RELATED PROBLEMS

As stated in Chapter 6, the IOM's did not identify the number of manhours nor the cost of correcting the problems. In this section, an estimate of the number of manhours to correct the problems is provided and that number is used to arrive at an approximate cost of these problems. Finally, some solutions to prevent design-related problems on future projects are proposed.

A fast-tracked project is justified by the saving of time through the use of the overlapped schedule. A shorter schedule is usually given priority over cost, and a certain amount of rework and redesign are expected. A goal of less than 5% of direct labor manhours is often set for rework. However, elimination or prevention of problems can lower initial construction costs through less rework.

B.1 Rework Manhours per Problem

Since the memos did not contain economic information, various approaches were used to bracket the costs of these problems. Similar to a real estate

appraisal where two or three different methods are used to establish a market value for a property, various methods are used to determine the average number of direct construction manhours associated with each problem. These methods are designated:

Method 1: Average Total Rework MH/Total Problems

Method 2: Analysis from Project Notices of Change

Method 3: Cost Engineer's Estimate

The first method takes the number of rework hours and divides by the number of problems. This average assumes equal manhours per problem and that all rework is recorded and accounted for by the memos. Table B.1 shows the results. The direct labor manhours (DLM), rework hours (rew), percentage of rework versus DLM (% rew), number of problems (#), and average manhours per problem (MH/Prob) for each unit are shown. Direct labor manhours and rework hours are taken from final labor reports provided by the construction contractor.

Table B.1--Average Manhours per Problem Using Method 1

	DLM (MH)	Rework (MH)	Rework (%)	Prob (#)	Average Rework (MH/Prob)
SRU	1326000	67000	5.1	506	133
HGU	1137000	88000	7.7	675	130
VPS	1323000	47000	3.5	405	116
H-OIL	2173000	143000	6.6	893	160
TOTAL	5959000	345000	5.8	2479	139

Results from the construction contractor's final report show rework percentages ranging from 3.5 for the VPS to 7.7 for the HGU. As stated before, the construction of the VPS unit was technically not as complex as the other units; therefore, its low rework percentage and MH/Prob average can be expected. The HGU had the highest percentage of rework, which is somewhat unexpected since the owner had previously participated in a similar project; however, the technology was not previously known to the design team. The H-Oil had the most rework and a higher than average percentage of rework, but the direct manhours were 60% greater than the other units and the most

complex as far as design and construction were concerned. It also had the largest average rework manhours per problem and due to the special equipment and piping required, this is not unexpected.

The second approach to determining the number of manhours per problem is by reviewing O'Connor's work (1983, 80-83). During his study, he reviewed 300 rework documents (these were not IOM's). These documents were construction contractor Project Notices of Change (PNC) that contained labor hours, and the documents were one level below the IOM's. The construction contractor used the PNC's to monitor all changes, while the IOM's were originated from the field when a problem could not be solved without home office help; therefore, all PNC's did not necessitate a memo being written.

In his study, he reviewed 300 documents in which 21,113 MH of rework were charged. These documents were mostly from the SRU, which was 52% complete at the end of the study.

The average number of manhours per problem was 70 MH/Prob. However, he discovered that 99 documents charged less than 20 MH/Prob each, while the other 201

documents had rework hours of 20,078--an average of 100 MH/Prob.

From these documents, approximate MH/Prob can be estimated for certain problem categories. The results are shown in Table B.2. This breakdown shows the variability among the categories and the reason for caution when using averages.

Table B.2--Average Manhours per Problem Category Using Method Two (After O'Connor)

Category	MH/Prob
Design	92
Drawings	105
Procurement	206
Schedule	223
Scope	267

The third method involved interviewing a cost engineer from the engineering staff (Bess 1987). He was familiar with the project and the memos. It was felt that he could provide one of the best estimates available of manhours needed to solve a problem identified in a memo.

Difficulties in estimating the rework hours necessary to solve a problem described in the memos are numerous. First, the problem descriptions are often very vague. Sometimes the memo refers to one piece of equipment, while others cover all the valves, pumps, etc. associated with one pipe run. Second, the impact of a change depends upon the time it is made. In the beginning of the project, a problem will often have less impact than a problem that occurs late in the project and involves numerous changes and disciplines. Third, the problem category itself affects the manhours involved. Examples of this variability can be observed in Table B.2. Finally, the crew size needed to complete rework as well as the efficiency of that crew directly affects the total manhours involved.

A sample of the problems for one unit was prepared. The sample was not randomly selected because typical problems from specific categories and disciplines needed to be reviewed and estimated. Two reasons dictated this approach:

1. Only an estimate could be provided for each problem based on problem descriptions that were not very detailed.
2. The variability of problems and resulting MH as shown in method two.

Problem selection is shown in Table B.3. The selection was based on organization, discipline, and problem category. From each category, typical problems based on problem descriptions were chosen. Selections were made from all categories except QA/QC and Procurement. QA/QC problems were not selected due to the small number of problems. Procurement problems were not selected because most vendor problems involve rework hours to replace or modify equipment which are backcharged to the vendor or the vendor itself solves the problem. Therefore, rework hours would not accurately reflect the actual owner time or finances involved.

Results from the interview are shown in Table B.4. Using this information, the average is 80 MH/Prob taking into account the 11 Scheduling problems, and 93 MH/Prob when the Scheduling problems are not included in the total.

Table B.3--Problems Selected from Each Problem Category

	Owner	Design Contr	Construction Contr	Total
Drawings	0	6	14	20
Schedule	1	6	4	11
Design	2	11	7	20
Scope	2	3	3	8
Specifications	0	3	3	6
Construction	3	7	5	15
Total	8	36	36	80

Table B.4--Average Manhours per Problem Category Using Method 3

Category	MH/Prob
Drawings	50
Schedule	0
Design	30
Scope	400
Specifications	20
Construction	100

Scheduling problems were thought by the expert to delay the project, but not to cause rework. The reasoning was that the crew would wait for the information before proceeding to complete the assigned task. However, in Table B.2, rework due to Scheduling problems involved incomplete engineering information and averaged 223 MH.

The discrepancy between these results illustrates the difficulty in obtaining accurate estimates and the importance of the timing of the problem. During a review or at the start of an activity, the crew can be reassigned to another activity, but if the error is discovered near the end of the activity or more information is needed to complete the job, rework hours may result. Therefore, the information in both tables is thought to be an accurate assessment of the respective documentation. In the case of the review by the expert, the problem descriptions in the IOM's indicated that they would not result in any rework.

Lacking more complete information and with a desire to be conservative on any economic impacts, Scheduling problems will be assumed to have delayed the project but not involve rework.

Table B.5 summarizes the results from the three methods.

Table B.5--Summary of Manhours per Problem

Method	MH/Prob
1	139
2	100
3	93

The decision was made to use an average of 100 MH/Prob for the economic analysis based on the following reasons:

1. As shown in Table B.2, a wide variation in MH/Prob exists between the problem categories
2. The lack of accurate information to determine MH/Prob from the memos
3. The accurate data provided by the PNC's

B.2 Cost of Problems

The cost of direct labor for this project was approximately \$15/MH (this includes \$12/MH plus 28% indirect cost for labor). Therefore, each problem cost an average of \$1500 to correct. Table B.6 summarizes the approximate cost of problems for each

unit and Table B.7 summarizes the approximate cost of problems classified by discipline of the originator.

Table B.6 shows that drawing problems had the largest cost--approximately \$1,024,500. This represents 33% of the cost identified through the memos.

Table B.6--Cost of Problems for Each Problem Category
(Amount in \$1000)

	SRU	HGU	VPS	H-OIL	TOTAL
Drawings	250.5	268.5	136.5	369.0	1024.5
Design	138.0	177.0	81.0	244.5	640.5
Scope	54.0	154.5	85.5	201.0	495.0
Procurement	90.0	84.0	42.0	100.5	316.5
Construction	55.5	64.5	54.0	103.5	277.5
Specifications	39.0	69.0	90.0	48.0	246.0
QA/QC	4.5	10.5	18.0	4.5	37.5
Total	631.5	828.0	507.0	1071.0	3037.5

Note: 1) Scheduling problems involved time and not direct cost.
2) Costs represent field labor costs and do not include re-engineering, owner or material costs.

Table B.7--Cost of Problems for Each Discipline
(Amount in \$1000)

	SRU	HGU	VPS	H-OIL	TOTAL
Piping	175.5	201.0	94.5	336.0	807.0
Instru*	189.0	217.5	138.0	229.5	774.0
Electrical	147.0	153.0	94.5	171.0	565.5
Equipment	43.5	100.5	70.5	154.5	369.0
Civil	22.5	91.5	79.5	117.0	310.5
Structural	43.5	43.5	22.5	51.0	160.5
Paint/Ins	9.0	10.5	7.5	10.5	37.5
Building	1.5	10.5	0.0	1.5	13.5
Total	631.5	828.0	507.0	1071.0	3037.5

* Instru = Instrumentation

Table B.7 shows that piping problems were the biggest expense in rework. Interestingly, Instrumentation was a close second. In fact, Instrumentation accounted for more of the rework than any other discipline in all units except the H-Oil unit. Together, these two disciplines represented 52% of the cost identified through the memos.

From these two tables, it can be observed that design-related problems cost approximately \$3 million

in direct labor costs. This number is probably a low estimate of the total rework expense because there has been no effort to account for the material costs associated with these problems, nor were there any studies made to determine the engineering and owner's costs involved in solving these problems. The documentation in its present state did not allow for this type of detailed evaluation. Therefore, although the figure of \$3 million is substantial by itself, it is a conservative estimate of the actual costs. Some researchers (see CII Quality Task Force) believe that the actual figure for rework is actually 10% or more of the total project cost.

B.3 Potential Solutions

Numerous suggestions can be made to lower this figure. The easiest way to prevent these problems is to eliminate them before they reach the field. This is emphasized by referring to the graph on costs and savings shown in Figure 2.2. The potential for saving money on the project is greatest in the beginning of the project and the costs at this point are the smallest. Therefore, potential methods to eliminate

problems will be provided for implementation during the design phase.

The most obvious counteraction is to add manpower. The question of where to add manpower would have to be decided by management. Does the owner increase his own staff for more detailed review, or require the design contractor to increase the engineers and draftsmen working on the project, or some combination of both alternatives?

The answer depends upon the assessment of the current situation of the owner's staff and the abilities of the design contractor. Piping, Instrumentation, and Electrical disciplines are the three areas where most problems occurred on this project, and that probably will not change. Therefore, these are the areas that should receive increased attention. It is not a surprise that Piping should receive increased attention, but Instrumentation can easily be overlooked. In this age of rapidly changing technology, this area will continue to gain importance and the owner must be prepared to keep abreast of those developments.

Drawing problems continue to be the most serious problem area once construction starts. Care-

ful and detailed review procedures could eliminate some of these problems. The other area to concentrate on is to freeze or minimize Scope and Design changes once construction starts. These two areas represented approximately 30% of the costs of rework, and that does not account for the ripple effect through the other problem categories nor the reduced productivity often associated with changes.

The second solution makes use of the computer. Computer usage was rather limited during the period in which this project was completed, but it has rapidly increased in the past few years. Before, only large contractors, design firms and owners made use of the computer. Now, most firms can afford and use a computer for some operations.

The next step as far as construction is concerned is the adoption of computer-aided drafting or design, usually designated CAD or CADD. For the purposes of this study, CAD will refer to computer-aided design where the drafting capability is assumed to be available and utilized. The usual procedure for design is to draft two-dimensional drawings of components with a model constructed either before or after these drawings. Advances in technology are starting

to allow production of three-dimensional drawings and representations of a model. According to Bishop (1987), one company is now marketing a system which has the ability to check piping between vessels. It will check alignment, size, pressure-ratings, interferences, and clear spaces for accessibility and safety. Many such systems are expected to evolve in the near future.

A system capable of performing these operations runs on a mainframe or possibly a supermini computer. The cost of this system is approximately \$1 million, which includes the software fee and the hardware. (Note: This is an example of one product, there are others on the market that vary in cost and capabilities. Management would have to decide which system best fits their needs.)

With such a substantial initial investment, the question becomes, How much would a system such as this save? The exact answer is hard to determine, but estimates are that CAD will save 5-10% of the total project cost. For a project similar to this one, that would translate into a savings of \$50-100 million--a substantial amount. This number represents the savings that would be gained throughout the entire

life cycle of a project. Later in this chapter, an analysis is done to determine how much of the labor cost for rework could be saved by using a CAD system.

To determine how much would be saved in rework hours, a review of what can be reduced is necessary. It is hard to tell which disciplines would directly benefit and to what degree, but piping, instrumentation, and electrical systems should have decreased problems.

When examining the problem categories, the biggest reductions would be in Drawings, followed by Design, Procurement, and possibly Scope. In the Drawings category, interferences, discrepancies, and omissions are problems that should be eliminated with CAD. Procurement problems would be reduced due to accurate bills of materials and accompanying drawings, but it would be hard to demonstrate this on this project and vendor errors would still be possible. Some design errors could be eliminated, while design changes might be minimized by having the ability to study changes and options earlier in the design process. The same reasoning can be applied to scope problems. Through design visualization, scope changes might be reviewed early in the conceptual phase and

eliminate the need to make changes later in the project. It is felt that specification problems, construction problems which are caused by construction forces, and quality problems would not be substantially reduced (or perhaps not at all) through the implementation of CAD.

In order to remain conservative, only the Drawing problems of interferences, discrepancies, and omissions are used to estimate the direct labor savings from this project with the use of CAD. Table B.8 shows the number of problems that could likely be eliminated through the use of CAD. Multiplying this number by the estimated \$1500/problem yields a potential savings of \$828,000. This represents a 25% decrease in the cost of direct labor manhours that were used on rework. Other costs which could be used in this analysis include material costs, owner costs, and other design costs.

Table B.8--Number of Drawing Problems Potentially
Eliminated by CAD

Unit	Drawing Problems
SRU	148
HGU	131
VPS	64
H-OIL	209
	—
TOTAL	552

A good CAD system involves a large initial cost and while projected savings are good, the investment would not be made for a single project. However, the results from this analysis show that the initial cost of a CAD system could almost be paid for with a project similar to this one and any further use of the system would result in larger savings for the investor.

B.4 Summary

This section examined the economic impact of design-related problems. Although the IOM's did not directly provide an accurate estimate of the rework manhours involved, three different methods were used

to estimate those manhours. Results differed for each method and variability existed between problem categories; therefore, an average of 100 MH/Prob was established. A more accurate estimate was not felt to be justified with this data.

Once the number of manhours to correct each problem was estimated, the cost of these problems could be established. Using \$15/HR as the cost for labor, the total cost of problems was approximately \$3 million. Drawing problems cost the owner approximately \$1 million while Design problems cost \$640,000. These two categories represented 55% of the total cost. The disciplines of Piping (\$807,000) and Instrumentation (\$774,000) accounted for 52% of the cost.

Using this information, several potential solutions for preventing problems or minimizing the impact of design-related problems were offered. The solutions concentrated on steps to take in the design phase where investment has the potential for the highest payback. These included (1) additional manpower on the owner's staff to review design documents, (2) additional manpower by the design contractor, and (3) use of Computer-aided design (CAD). The

additional manpower should emphasize minimizing drawing and design errors, especially in the Piping, Instrumentation, and Electrical disciplines.

Calculations showed that over \$828,000 could be saved in direct construction labor manhours. This figure does not include the drafting or design time that revisions and changes entail, so it should be a conservative figure. Using this figure, it can be observed that a CAD system can be economically justified with one project of this scope and increased savings would result with increased use.

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This dissertation was typed by the author.